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Executive Summary of Systems Analysis to Develop Future Civil Aircraft Noise Reduction Alternatives

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This executive summary contains the results of the study "System Analysis to Develop Future Civil Aircraft Noise Reduction Alternatives" performed by Wyle Laboratories under contract no. DOT-FA77-WA 3900 (July 1980). The original study first developed and examined a set of projected scenarios of U.S. carrier aircraft fleet compositions for three planning years: 1980, 1990, and 2000 (hereinafter referred to as the planning years). An analysis of the costs and benefits of alternative methods of achieving noise reductions around airports was then made, based on information available in 1979. Forecasts may not necessarily represent present (October 1981) situations. The study involved six specific technical areas, for which separate volumes were prepared: Volume I - Aircraft Classification Specification, Volume II - Aircraft Certification, Volume III - Technology Assessment, Volume IV - Definition of Flight Path Options, Volume V - Land Use Options, and Volume VI - Cost/Benefit Analysis.

Due to the large amount of data collected for the study, the FAA determined that it would not be economically feasible to publish such a voluminous report.

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METRIC CONVERSION FACTORS

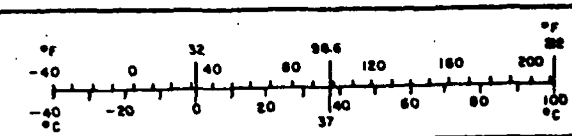
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ABBREVIATIONS AND SYMBOLS

ADV	advanced
AFL	above field level
ANAP	Aviation Noise Abatement Policy
AST	advanced supersonic transport
CTOL	conventional takeoff and land aircraft
dB(A)	A-weighted noise (decibels)
EPNL	effective perceived noise level
FAR	Federal Aviation Regulation
Fn/δ	referred thrust
FPM	feet per minute
HN	high bypass ratio narrow body
HW	high bypass ratio wide body
HWT	high bypass ratio wide body treated jet
ICAO	International Civil Aviation Organization
KEAS	airspeed (knots)
Ldn	day/night average sound level
LDN	long duct nacelles
LN	low bypass ratio narrow body
LNT	low bypass ratio narrow body treated jet
LNU	low bypass ratio narrow body untreated jet
LTOSL	average takeoff certification levels
MCL	maximum climb
MLW	maximum loading weight
MPH	miles per hour
MTOGW	maximum takeoff gross weight
MTOW	maximum takeoff weight
$N1/\sqrt{\theta_T}$	engine fan speed corrected for air temperature
NEF	noise exposure forecast
NII	noise impact index
OEW	operator's empty weight
PNdB	perceived noise (dB)
PNL	perceived noise level
PNLT	perceived noise level tone-corrected
RPM	revolutions per minute
RTM	revenue ton mile
SEL	sound exposure level
SFC	specific fuel consumption
STOL	short takeoff and landing aircraft
STR FUS	stretched fuselage
T/W	thrust to weight
V_s	velocity
VTOL	vertical takeoff and landing aircraft
W_f	fuel flow rate

SECTION 1

INTRODUCTION

This executive summary contains the results of the study "System Analysis to Develop Future Civil Aircraft Noise Reduction Alternatives" performed by Wyle Laboratories under contract no. DOT-FA77-WA 3900 (July 1980). The original study first developed and examined a set of projected scenarios of U.S. carrier aircraft fleet compositions for three planning years: 1980, 1990, and 2000 (hereinafter referred to as the planning years) based on information available up through 1979. An analysis of the costs and benefits of alternative methods of achieving noise reductions around airports was then made. The study involved six specific technical areas, for which separate volumes were prepared: Volume I - Aircraft Classification Specifications, Volume II - Aircraft Certification, Volume III -Technology Assessment, Volume IV - Definition of Flight Path Options, Volume V - Land Use Options, and Volume VI - Cost/Benefit Analysis.

In Volume I, an aircraft classification system was devised that categorized, for noise certification purposes, all civil aircraft types and the number expected to be in operational use during the planning years. The classifications ultimately selected for use throughout this study categorized aircraft into three groups: air carrier (commercial), general aviation, and helicopters.

Volume II examined current takeoff and landing flight procedure requirements, level flyovers as alternatives or replacements for the existing takeoff and landing requirements, and the potential role of static engine noise testing for noise certification. Detailed data acquisition, analysis or correction requirements for test day conditions, tones or background noise correction methods as described in FAR Part 36 were not considered. Noise certification procedures considered for adoption were discussed.

The purpose of Volume III was to generate cost effective source noise reduction options that were technologically practical. These source noise reduction options were then compared on a cost-effectiveness basis with other approaches to aviation noise abatement. Noise reduction methods, acoustic analysis and economic analysis for representative aircraft configurations in the air carrier, general aviation and helicopter fleets expected to be operating in the planning years were all considered. The study output constituted a major input into the system-wide cost/benefit tradeoffs that were discussed in Volume VI.

In Volume IV, flight path options for air carrier, general aviation, and helicopter aircraft were examined. Several geometric flight path

options for air carrier aircraft were considered for use in the study. These were evaluated to determine which options would provide acceptable noise relief for each of the aircraft. Two takeoff flight paths and one approach flight path were selected for detailed study. A similiar but less detailed study of flight path options was performed for general aviation aircraft and helicopters.

Volume V contained a review of land use planning methods available to state, local, and Federal agencies for reducing aircraft noise exposure of populations in the vicinity of airports. Twelve land use options were examined, based on a review of the literature, to determine their compliance with the requirements set out for including land use options in the unit-cost analysis. These requirements, briefly summarized, were that the selected land use options should be applicable nationwide, be amenable to public administration, provide benefits in terms of direct reduction of noise exposure, and result in costs and benefits that could be readily quantifiable for use in the cost-benefit analysis. Of the options examined, three met these requirements: Relocation, Improvement of Sound Insulation of Existing Dwellings, and National Changes to Building Codes.

Volume VI described the methodology and findings of a cost-benefit analysis of alternative methods of reducing noise impact around airports, based on information available in 1979. The study was based on projections of the U.S. carrier fleet expected to be operating at the nation's network of airports during the planning years. Cost and noise impact benefits associated with aircraft technology changes, modified operational procedures for departure flights, and land use options applicable to residential areas in the airport environment were compared. The methodology involved an application of each of these options, including baseline cases, to 14 separate sample airports representing the nation's airport network. Benefits were assessed by evaluating the reduction in Noise Impact Index (NII) over a wide demographic sample representing the noise impacted residential population.

SECTION 2

AIRCRAFT CLASSIFICATION SPECIFICATIONS (VOLUME I, TASK I)

The major goal of Task I was to devise an aircraft classification system which would categorize, for noise certification purposes, all civil aircraft types expected to be in operational use during the planning years. In order to achieve the objective of noise certification, current and predicted aircraft were subdivided into families or classes for noise abatement technology evaluation. The number of aircraft classes, held to a minimum for practical purposes, had to be unambiguous and mutually exclusive. Existing aircraft classification specifications from Federal agencies and various national and international organizations were researched and considered for adoption. However, after examining their classification specifications, none of them were found to be suitable for noise certification purposes.

GENERAL AIRCRAFT CLASSIFICATION

Civil aircraft have various sizes, shapes, and noise characteristics. For noise regulation, three factors had to be taken into account since they have a major influence on aircraft characteristics. These factors were:

Lift System: Air vehicles can be categorized as fixed-wing, rotary-wing, or powered-lift aircraft by their lift system. The powered-lift aircrafts were not included in this report since this technology could not be commercially developed through the year 2000 from a cost-effectiveness standpoint.

Propulsion System: Propellers and rotors on aircraft may be driven by either turbine engines or reciprocating engines.

Vehicle Weight: Weight of an aircraft governs the amount of thrust required for both takeoff and cruise speed. Gross weight only was found to be a useful parameter to further subdivide the major classes of aircraft based on operator type.

Thrust-to-weight ratios(T/W) were not included in the classification scheme even though T/W ratios are widely used to measure aircraft takeoff performance since the parameters of lift system, propulsion system, and gross weight already contain an imputed T/W value. Based on these factors, the following general aircraft classification was initially determined:

TURBOJET-POWERED AIRCRAFT
- Subsonic Transports
- Supersonic Transports
- Business Jets
- Short Takeoff and Landing Aircraft

PROPELLER-DRIVEN AIRCRAFT
- Conventional Takeoff and Landing Aircraft
- Short Takeoff and Landing Aircraft

HELICOPTERS

This general aircraft classification was further categorized for use throughout this study into three groups: air carrier (commercial), general aviation, and helicopter.

AIR CARRIER AIRCRAFT

For air carrier aircraft, 29 gross characteristics were selected to describe these aircraft. These descriptors were subdivided into four major categories:

Aircraft Geometry	-	Number of Engines/Location Wing Span Trapezoidal Wing Area Aspect Ratio Overall Length Overall Height Leading Edge High Lift System Trailing Edge High Lift System Sweep of 25% Chord
Weight Data	-	Maximum Takeoff Gross Weight, MTOGW Operator's Empty Weight, OEW Maximum Landing Weight, MLW Number of Passengers Selected Payload
Power Plant Data	-	Engine Type Uninstalled Sea Level Static Thrust Uninstalled SLS Bypass Ratio
Performance Data	-	Wing Loading Based on MTOGW SLS Thrust-to-Weight Ratio Rotation Speed FAA Takeoff Field Length Initial Cruise Altitude Capability Cruise Altitude, Long Range Maximum Mach at Start of Cruise Long Range Mach at Start of Cruise SFC at Start of Cruise Range with Selected Payload Approach Speech at MLW FAA Landing Field Length

Advanced technologies to improve the aircraft fuel consumption, efficiency, and operation costs were expected to be introduced into the design of new aircraft by the years 1990 and 2000. These advanced technologies would include:

Fuel-Conserving Engines
- Improved Specific Fuel Consumption
- Mixed - Flow Nacelle Designs
- Advanced Turboprops

Decreased Aircraft Drag
- Supercritical Air Foils
- Increased Aspect Ratio
- Lower Cruise Speed
- Active Controls (To Reduce Size and Weight of Surfaces)
- Reduced Skin Friction (Laminar Flow Control)
- Winglets

Decreased Aircraft Weight
- Use of Advanced Lightweight Composite Materials
- Lowered Structural Weight (Using Reduced Sweep and Thicker Supercritical Wing)
- All-Wing Concepts

Based on information available through 1979, six representative aircraft were forecast to be in the 1980 air carrier inventory (see Table 1). Aircraft forecast to be added to the fleet in the years 1990 and 2000 are also shown in Table 1.

Total aircraft in the service of U.S. Air carriers for the years 1980, 1990, and 2000 were estimated based on the Douglas Aircraft Company traffic forecast for the 32 U.S. airlines as of January, 1977 and reviewed with FAA. These estimates were subsequently revised as part of a continuous updating process. Table 2 shows the air carrier fleet compositions which were used in the cost benefit analyses.

Freight aircraft have not been included in these forecasts. Freight aircraft traffic in the U.S. is predicted to grow at an average annual rate of 8.7 percent from 1976 to 2000.

GENERAL AVIATION AIRCRAFT

For general aviation aircraft, gross aircraft characteristics were used to select the representative aircraft for three types in the general aviation fleet: (1) fixed wing, piston powered, single-engine aircraft, (2) fixed wing, multi-engine aircraft, and (3) general aviation jet aircraft. These gross aircraft characteristics are listed in Table 3 under the same four categories as specified for air carrier aircraft.

With respect to the study years 1990 and 2000, considerations were given to performance and fuel efficiency of the general aviation fleet. In addition to increased model numbers, gross characteristic changes have also been anticipated for the representative aircraft, as noted below.

TABLE 1

REPRESENTATIVE AIRCRAFT MODELS SELECTED FOR USE IN FORECASTS FOR THE U.S. CIVIL AIRCRAFT FLEET IN THE PLANNING YEARS 1980, 1990 AND 2000

1980 Fleet	1990 Fleet	2000 Fleet
Two Engine Low Bypass Ratio Narrow Body (2LN)	Two Engine Low Bypass Ratio Narrow Body (2LN)	Two Engine Prop Fan Narrow Body (2LN)
Three Engine Low Bypass Ratio Narrow Body (3LN)	Advanced Two Engine High Bypass Ratio Narrow Body (2HN)	Two Engine High Bypass Ratio Narrow Body (2HN)
Four Engine Low Bypass Ratio Narrow Body (4LN)	Two Engine High Bypass Ratio Wide Body (2HW)	Three Engine High Bypass Ratio Wide Body (3HW)
Three Engine High Bypass Ratio Wide Body (3HW)	Advanced Two Engine High Bypass Ratio Wide Body (2HW)	Four Engine High Bypass Ratio Wide Body (4HW)
Four Engine High Bypass Ratio Wide Body (4HW)	Three Engine High Bypass Ratio Wide Body Stretch (3HW)	Four Engine Low Bypass Ratio Narrow Body (4LN)
Turboprop Two Engine Narrow Body	Four Engine High Bypass Ratio Wide Body Stretch (4HW)	
	Four Engine High Bypass Ratio Narrow Body Retrofit (4HN)	
	Four Engine High Bypass Ratio Wide Body	
	Turboprop Four Engine Narrow Body	

TABLE 2

REVISED U. S. AIR CARRIER PASSENGER AIRCRAFT FLEET

Aircraft Description	1980	1990	2000
Propeller	53	13	13
4HW (750 PAX)	-	-	45
4HW (550 PAX)	-	11	119
4HW (380 PAX)	114	234	251
3HW (380 PAX)	-	139	411
3HW (280 PAX)	273	408	312
2HW (200 PAX)	16	570	1284
4LN (140 PAX)	244	59	36
2HN (200 PAX)	-	394	1213
3LN (140 PAX)	1068	812	711
2LN REFAN (140 PAX)	13	140	162
2LN REFAN STR (140 PAX)	2	56	56
2LN (105 PAX)	589	248	199
Grand Total:	2372	3084	4812

PAX = number of passengers

TABLE 3.- GROSS AIRCRAFT CHARACTERISTICS USED FOR SELECTION OF REPRESENTATIVE GENERAL AVIATION AIRCRAFT

Gross Characteristics Categories	Fixed Wing, Single- and Multi-Engine Aircraft	Jet Aircraft
Aircraft Geometry	Overall Length (FT) Overall Height (FT) Overall Wing Span (FT) Wing Area (SQ FT) Aspect Ratio	Overall Length (FT) Overall Height (FT) Overall Wing Span (FT) Wing Area (SQ FT) Aspect Ratio
Weight Data	Maximum Takeoff Weight(LB) Standard Empty Weight (LB) Useful Load (LB) Number of Seats (Includes Crew)	Maximum Ramp Weight (LB) Maximum Takeoff Weight (LB) Maximum Landing Weight (LB) Standard Empty Weight (LB) Useful Load (LB) (Includes Crew) Number of Seats (Includes Crew)
Power Plant	Designation Maximum Power (BHP) at Specified RPM	Designation Number of Engines S.L. Static Thrust/Engine Bypass Ratio S F C (LB/HR/LB Thrust)
Performance Data	Wing Loading (LB/SQ FT) Power Loading (LB/HP) Takeoff Over 50 Feet (FT) Maximum Level Speed (KTAS) Maximum Cruise Speed (KTAS) at Specified Altitude (FT) Landing Over 50 feet (FT)	Wing Loading (LB/SQ FT) Thrust Loading (LB/LB Thrust) Takeoff Field Length (FT) Maximum Cruise Altitude (FT) Range: Maximum Cruise Power, 43,000 FT, Full Fuel, 45 Minute Reserves (Nautical Miles) Cruise Mach Number: @43,000 feet, @Mid-Cruise Weight Maximum Cruise Speed (KTAS), @25,000 feet @mid-cruise weight Landing Field Length (FT)

Class of General Aviation Aircraft	Representative Aircraft	Gross Characteristics	Year 1980	Year 1990	Year 2000
Fixed Wing, Single-Engine	Cessna 172/ Skyhawk	Max. Takeoff Wt. (LB)	2,300	2,350	2,400
		Max. Power (BHP)	160	165	170
Fixed Wing, Multi-Engine	Cessna 340	Max. Takeoff Wt.(LB)	5,990	6,090	6,190
		Max. Power (BHP)	310	320	330
Fixed Wing, Jet-Powered	Cessna Citation II	Make Takeoff Wt. (LB)	13,300	13,300	14,000
		S.L. Static Thrust/ Engine	2,500	2,700	2,900

The general aviation fleet forecast has been based on two selected forecasting methods: (1) aircraft unit increase from 1956-78 for single and multi-engine aircraft and from 1966-77 for jet-powered general aviation, and (2) annual percentage increase in aircraft for the same time period. Since wide fluctuations have been found from both methods, a cumulative average was taken to account for the variations. A general aviation fleet forecast based on cumulative average data is summarized below:

Year	Single-engine fleet	Multi-engine fleet	Jet fleet
1980	158,200	26,800	2,300
1990	209,600	37,600	3,800
2000	272,100	49,500	5,200

HELICOPTERS

The gross characteristics for selection of representative helicopters are listed below:

Rotorcraft Geometry - Max. Height (Ft)
Rotor Diameter (Ft)
Max. Length @ Unfolded Blades (Ft)
Blade Chord Length (Ft)
Solidity
Number of Blades

Weight Data - Empty Weight (LB)
Normal Gross Weight (LB)
Number in Crew
Number of Passengers

Power Plant Data - Horse Power/Engine
Engine Number
Make
Model

Performance Data - Max. Speed (MPH)
Rotor Tip Speed (FPS)
Hover Ceiling in Ground Eff. (Ft)
Still Air Range (Miles)

According to their gross weight, 3 kinds of helicopters have been classified for this study:

Classification	Light	Medium	Heavy	
Rotor type	Single Rotor	Single Rotor	Tandem Rotor	Single Rotor
Representative Rotorcraft	Hughes 500 C	S 76	CH 410	S61L
Median weight (LB)	3,000	8,000	50,000	

Changes in gross helicopter characteristics expected in the years 1990 and 2000 are shown below:

Median Weight	-	3,000 lb. in 1980 for Light Helicopters rising to 6,000 lb. in 2000
		8,000 lb. in 1980 for Medium Helicopters rising to 14,000 lb. in 2000
		50,000 lb. in 1980 for Heavy Helicopter rising to 80,000 lb. in 2000.
Cruise speeds	-	150 miles per hour in 1980
		160 MPH in 1980
		170 MPH in 2000
Rotor Speeds	-	700 FPS at present
		600 FPS expected by 1980
		600 FPS for cruise and 450 FPS for hover by 2000.

Civil helicopters have increased at an average annual rate of approximately 12 percent during the past 15 years (1960-75). This is about 2½ times higher than fixed-wing aircraft (5% annual increase rate during the 1966-1975 period). The rate of increase of the U.S. helicopter fleet is not expected to continue at this high level because of the shortage of necessary material resources for helicopter production, facilities for maintenance, and trained helicopter pilots. However, after reviewing the improvements in technology, a future rate of growth of 7 percent in fleet size appears reasonable. Based on information available up through 1979, this will produce a total helicopter fleet size of 7,200 in 1980, 14,200 in 1990, and 27,900 in the year 2000. The composition of this civil helicopter fleet is expected to change as follows:

Percent of total helicopters in each class

Year	Light	Medium	Heavy
1975	90	9	1
2000	83	15	2

SECTION 3

AIRCRAFT CERTIFICATION
(VOLUME II, TASK II)

The purpose of this task was to review the past and ongoing aircraft noise certification concepts proposed by the Federal Aviation Administration (FAA), the International Civil Aviation Organization (ICAO), and others, and to define noise certification methods appropriate for the different classes of aircraft considered in this study.

A number of general and specific concepts in noise certification were examined. These included current takeoff and landing requirements, level flyovers as alternatives or replacement of the takeoff and landing requirements, and the potential role of static engine noise testing for noise certification.

The noise certification procedures adopted for this study consisted of two elements: (1) an initial static engine/nacelle test to certify an engine for the absence of significant pure tone components or to provide measured data, when required, to cover an acoustical change involving only the engine/nacelle combination, and (2) a level flyover test to certify an aircraft for noise after translation of the measured data to fixed measurement points on the ground under maximum noise flight conditions. For the latter test, maximum gross weight was considered to be the appropriate aircraft parameter to use for determining acceptable noise levels.

OBJECTIVE OF NOISE CERTIFICATION PROCEDURES

The objective of the current Federal Aviation Regulation (FAR) Part 36 noise certification procedures is to ensure that newly designed aircraft will not be any noisier than existing aircraft and will employ all economically reasonable and technically practical noise abatement hardware devices in their design.

Revisions of the current noise certification procedures may be desirable because:

1. while the certification process must continue to ensure incorporation of all economically reasonable and technically practical hardware in aircraft design, aircraft noise data potentially available from certification testing are also an essential requirement to the airport planning process.

2. poor agreement sometimes exists between variations in takeoff certification noise levels for various aircraft types and corresponding average noise monitoring levels for aircraft in commercial service. This is primarily due to differences

between certification flight procedures and operational flight procedures actually practiced by the airlines and other operators.

3. the presently defined certification procedures are expensive and test locations difficult to obtain.

4. parameters that relate more directly to overall productivity of the aircraft, such as payload, range, and fuel efficiency, may be included in the consideration of a more desirable noise level criteria.

The ultimate objective of the FAR Part 36 aircraft certification process is to control near-airport community noise levels. The general practice in industry in complying with legal noise requirements is to specify measured or calculated certification noise levels within 0.1 dB. Manufacturers often expend substantial resources to meet the legal requirements, sometimes by only a small margin. Certification test noise levels have been considered a measure of the single event aircraft noise source levels near airports and hence related directly to community noise impact.

An aircraft that is in compliance with FAR Part 36 Regulations, and thus with lower certification noise levels, would be expected to have less of a noise impact on the community. Airlines are often under public pressure to reduce noise levels and are legally required to replace aircraft that cannot meet certain certification noise levels. However, some anomalies do appear when investigating the relationship between certification noise levels and the noise impact on the nearby airport community. Two representative parameters have been examined: (1) single event noise contour areas and (2) single event levels from airport monitoring systems. A strong relationship was found between these representative parameters and certification noise levels for the approach situation. A less satisfactory relationship existed for the takeoff data available.

EFFECTIVENESS OF CERTIFICATION PROCEDURES

In summary, the current FAR Part 36 noise certification procedure has been effective in helping to turn around a growing trend in noise impact around airports. The actual certification levels measured for approach can be expected to correlate closely with single event landing contour areas and single event levels under the approach path for all jet aircraft regardless of the level of technology. For takeoff, this close correlation seems to also hold within a given level of aircraft/engine technology when the average of the sideline and takeoff certification levels is related to takeoff contour area.

However, this relationship varies substantially between technology levels so that takeoff certification levels do not appear to be a reliable indicator of community noise impact across all levels of aircraft/engine technology. Nevertheless, the existing certification method still provides

a means of controlling source noise characteristics within a given level of technology - a capability which was inherent in its initial concept and, in fact, was all that noise certification was originally designed to accomplish.

ALTERNATIVE CERTIFICATION METHODS

There are several alternative choices for the primary elements of aircraft noise certification, such as noise goals used to achieve a specified target for the population impacted with a given noise contour level or used to specify a simple definition of noise levels. Reference conditions, such as aircraft weight and flight procedures, must also be determined. Finally, any noise certification goal must have well-defined applicability criteria such as for newly produced aircraft or for all aircraft in the fleet. These, together with alternative methods of noise measurement, were studied.

Based on the results of this study, up through 1979, the following possible changes to existing certification procedures were considered:

1. Use of a static pure tone screening test of each engine/nacelle combination prior to flight testing,

2. Use of level flyover tests to acquire data for the computation of certification levels and community noise data banks for computer contour programs, such as INM (Integrated Noise Model),

3. Preferred use of a simpler time-integrated A-weighted noise metric for flyover tests,

4. Provisions to minimize effect of ground reflection anomalies in data, and

5. For propeller driven aircraft, use of a prescribed power setting expressed as a single specific percentage (uniform over all models of similar design) of maximum rated power.

SECTION 4

TECHNOLOGY ASSESSMENT AND PRELIMINARY GOALS DEFINITION (VOLUME III, TASK III)

The major activity of Task III can be summarized as follows:

A. Identify and catalog source noise reduction technology as well as aircraft performance parameters and associated acoustical benefits for the planning years.

B. Evaluate the acquisition, operational (including maintenance cost), and total life cycle cost due to the acoustic modification of each class of aircraft.

C. Determine the impact of acoustic modification on aircraft mission, marketability, and economics.

D. Identify changes in the aircraft design and performance characteristics which would result from the application of noise abatement technology so that the general physical and operational features of future configurations can be examined.

AIR CARRIER AIRCRAFT

Representative Aircraft Performance

A total of 14 air carrier aircraft classes were considered in this study for the planning years. The 14 aircraft classes and explanation of the code names are shown in Table 4. Aircraft were evaluated by conducting a mission analysis for each candidate aircraft. Advanced technology that was available has been incorporated into the design of each aircraft at the time of its introduction to the fleet. The resultant effects on performance have been analyzed and compared to baseline aircraft configurations.

Technology Options

Year 1980 - Representative Aircraft

The foremost technology advancement that differentiates the late 1970's aircraft fleet in terms of acoustics and performance from its predecessors was the advent of the high bypass ratio engines. The predicted 1980 representative aircraft included sound absorbent material in the nacelle of the low bypass engines which had a negligible effect on weight and performance of most of the aircraft.

TABLE 4

CODE NAME DESCRIPTIONS
FOR
14 REPRESENTATIVE AIRCRAFT CLASSES

Year	Code Name	Explanation
1980 Existing Aircraft	2LN	2 Engine Low-Bypass Ratio Narrow Body
	3LN	3 Engine Low-Bypass Ratio Narrow Body
	4LN	4 Engine Low-Bypass Ratio Narrow Body
	3HW	3 Engine High-Bypass Ratio Wide Body
	4HW	4 Engine High-Bypass Ratio Wide Body
1990 New Aircraft	2LN (Refan)	2 Engine Low-Bypass Ratio Narrow Body
	2HN	2 Engine High-Bypass Ratio Narrow Body
	2HW	2 Engine High-Bypass Ratio Wide Body
	2HW (Advanced Aerodynamics)	2 Engine High-Bypass Ratio Wide Body
	3HW (Stretched Fuselage)	3 Engine High-Bypass Ratio Wide Body
	4HW (Stretched Fuselage)	4 Engine High-Bypass Ratio Wide Body
2000 New Aircraft	2HN (Stretched Fuselage)	2 Engine High-Bypass Ratio Narrow Body
	3HW (Stretched Fuselage, Advanced Aerodynamics)	3 Engine High-Bypass Ratio Wide Body
	4HW (Stretched Fuselage, Advanced Aerodynamics)	4 Engine High-Bypass Ratio Wide Body

Year 1990 - Representative Aircraft

The 1990 fleet aircraft was assumed to include 1980 aircraft retrofitted to incorporate acoustic and performance technology advancements, derivative aircraft that incorporate technology and design improvements, and new aircraft that incorporate technology advancements feasible for the time period.

The 1980 fleet was divided into two categories: the low bypass-engined and the high-bypass aircraft. The 2LN and 3LN low bypass engined aircraft were considered to be operational in the 1990 fleet. The retrofitted versions of these aircraft included the installation of refanned low bypass engines.

All high-bypass engined aircraft (2HW, 3HW and 4 HW) were assumed to be operational in the 1990 fleet. The retrofitting of these aircraft consisted of modifying the engine nacelle from the current short fan duct separate flow to that of a long duct nacelle with a mixer. The derivative aircraft included in the 1990 fleet is the 2LN refan representative aircraft, redesigned to the extent that it can fully utilize the performance benefits associated with the refan engine. The new representative aircraft in the 1990 forecast include the 2HN, 2HW ADV, 3 HW STR, and the 4HW STR.

Year 2000 - Representative Aircraft

All of the representative aircraft introduced in 1990 were assumed to also be in the year 2000 fleet. The new aircraft in the 2000 fleet included the 2HN STR, 3HW STR/ADV and the 4HW Large. From a performance standpoint, the advanced technology, which improves aerodynamic, and propulsive efficiency and reduces weight, results in improved fuel efficiency.

All of the high bypass retrofit aircraft with long duct nacelles and mixers were more fuel efficient and had more range capability than the baseline aircraft because of increased aerodynamic and propulsive efficiency. The new aircraft in 1990 and 2000 were predicted to benefit from increasingly advanced technology, producing significantly lower fuel burned per pound of payload per nautical mile.

Acoustic Analysis

Seven noise reduction features were considered for 13 of the 14 aircraft classes noted in Table 4 (not 4LN). The noise reduction features applied to each representative aircraft are presented in Table 5. Fifty-four noise maps (noise-distance power relationships) were developed for the aircraft classes with and without noise reduction features. The noise maps were represented both graphically and analytically. Noise map data base was either flyover or static test and/or both. The most promising noise reduction alternatives appear to be the new aircraft that utilize the refan, high bypass-ratio, and clip-fan engine technology and new aircraft equipped with long-duct nacelle and mixer configurations.

TABLE 5

NOISE REDUCTION TECHNOLOGY FEATURES
FOR YEARS 1980, 1990, and 2000

Representative Aircraft Classes

Noise Reduction Technology Features	2LN	3LN	3HW	4HW	2LN (Refan)	2HN	2HW	2HW (Adv Aero)	3HW (Str Fus)	4HW (Str Fus	2HN (Str Fus)	3HW (Str Fus Aero)	4HW (Str Fus Aero)
1. Long duct nacelles with increased acoustic treatment	x	x	x	x	x		x	x	x	x		x	x
2. Improved acoustical treatment for turbomachinery noise absorption	x	x	x	x	x		x	x	x	x		x	x
3. Internal mixer nozzles for jet noise reduction	x	x	x	x	x		x	x	x	x		x	x
4. Refanned engines for reengine	x	x			x								
5. New high-bypass-ratio engines						x					x		
6. Modified takeoff and landing aerodynamic configuration (supercritical wing)						x		x				x	x
7. Improved high-lift systems (flaps and slats)						x	x	x			x	x	x

GENERAL AVIATION PROPELLER AIRCRAFT

Noise Reduction

To evaluate the possible noise reduction features and their impact on performance and other parameters, a total of six configuration changes (SE-2 through SE-7) from the baseline (SE-1) were analyzed for the single-engined fixed wing aircraft and seven configuration changes (ME-2 through ME-8) from the baseline (ME-1) for the twin-engined aircraft category. These study configurations are summarized in Tables 6 and 7. A typical mission was defined for both single and twin-engined propeller aircraft categories. Each of the study configurations was flown on the typical mission and comparisons were made with the baseline configuration. This provided information on the impact on time to climb and cruise speed performance as well as fuel consumption to carry a given payload over a typical stage length. No measured data was available on the impacts of three versus four bladed propellers (ME-7 versus ME-8 in Table 7) on noise reduction.

Weight Impact

The impact of implementation of the configuration changes noted in Tables 6 and 7 on standard empty weight was calculated. This information was used in the typical mission performance calculations to determine the effect on mission capabilities. All configurations experienced a weight penalty which reduced useful load from 3½ to 7 percent. This produced severe limitations on mission capabilities.

Impact on Performance and Mission Capabilities

The impact of implementation of the configuration changes noted in Tables 6 and 7 on key performance and mission characteristics was calculated for each study configuration. Takeoff over 50 feet and maximum rate of climb were key performance items affecting aircraft safety and mission versatility. The single-engined study aircraft showed reductions in climb performance varying from 1.3 to 16.9 percent. Safety and ground noise exposure were adversely affected. The twin-engined studies showed reductions of 1.0 to 7.9 percent for two engine climb and 2.9 to 16.2 percent for one engine climb.

Impact on Fuel Efficiency and Cost

Fuel efficiency was adversely affected by implementation of the configuration changes noted in Tables 6 and 7. In the single-engined category, fuel consumption for the typical mission increased from 1 to 6 percent and for the twin-engined category the increase varied from 1 to 3 percent. This deterioration was significant relative to both fuel conservation and mission capability. Operating cost increases were estimated to range from 2 to 8 percent for the 13 study configurations. Acquisition costs were 4.5 to 11.5 percent higher than the baseline aircraft.

TABLE 6

STUDY CONFIGURATIONS
SINGLE-ENGINED PROPELLER AIRCRAFT CATEGORY

CONFIGURATION	TAKEOFF HP	TAKEOFF RPM	PROPELLER DIAMETER (INCHES)	ACTIVITY FACTOR PER BLADE	ROTATIONAL TIP SPEED (FPS)
Baseline, SE-1	160	2700	75	85	884
SE-2	160	2550	75	85	834
SE-3	160	2550	75	95	834
SE-4	160	2550	75	105	834
SE-5	160	2550	70	85	779
SE-6	160	2550	70	95	779
SE-7	160	2550	70	105	779

TABLE 7

STUDY CONFIGURATIONS
TWIN-ENGINED PROPELLER AIRCRAFT CATEGORY

CONFIGURATION	TAKEOFF HP	TAKEOFF RPM	PROPELLER DIAMETER (INCHES)	ACTIVITY FACTOR PER BLADE	ROTATIONAL TIP SPEED (FPS)	NO BLADES
Baseline, ME-1	310	2700	76.5	89	901	3
ME-2	310	2575	76.5	89	860	3
ME-3	310	2575	76.5	100	860	3
ME-4	310	2575	76.5	110	860	3
ME-5	310	2575	71.5	89	803	3
ME-6	310	2575	71.5	100	803	3
ME-7	310	2575	71.5	110	803	3
ME-8	310	2575	71.5	89	803	4

Acoustic Analysis

The prime noise reduction technology considered on both the single- and twin-engined propeller aircraft was reduced rpm. This feature was evaluated with feasible propeller diameter and activity factor variations. Flyover noise reduction changes were estimated together with the impact on performance, weight, safety, fuel consumption, and economics.

In achieving lower noise levels through reduced tip speeds, reduced rpm had less adverse impact on performance than did reduced diameter. In both cases, it would be desirable to use propellers which produce more thrust per horsepower than current production designs in order to minimize performance deterioration.

One approach to recover performance losses when using a slower rpm is to increase propeller diameter, as diameter has a strong influence on low speed performance. To accommodate larger propeller diameters would require new longer gears and new gear well configurations, and even then the performance losses may not be totally recoverable because of these weight and design changes. A critical factor involved in achieving reduced noise levels through lower tip speeds is the availability of suitable engines. The majority of the propeller aircraft U.S. fleet has engines rated at 200 horsepower or less. No certified gear engines are now in production in this low power class.

GENERAL AVIATION BUSINESS JET AIRCRAFT

Representative Aircraft

Four study features were considered for reducing noise on aircraft in the general aviation jet aircraft category. These features included multi-element exhaust nozzles, lined ejectors, inlet liners and tailpipe liners.

Acoustic Analysis

The primary noise source of general aviation jet aircraft is the engine. The two principal sources of engine noise are the jet exhaust and the fan/compressor. The exhaust noise of business turbojet engines can be reduced through the use of multi-element exhaust nozzles. The noise reduction of such nozzles on fan engines is relatively small compared to turbojets. Weight, cost and performance penalties are introduced. The use of lined ejectors in conjunction with multi-element nozzles' provides little additional noise reduction at greatly increased weight and performance penalties. Inlet duct lining is a means of reducing noise, especially discrete frequencies. The use of lined exhaust tailpipes, in conjunction with multi-element exhaust nozzles, can provide some additional noise reduction especially on straight turbojet engines.

Replacement engines were not evaluated as a means of noise reduction because it is unlikely that further increases in engine bypass ratios will offer further decreases in noise level. Aircraft performance penalties increase rapidly when nozzles are designed for higher noise suppression.

The FAR 36 noise levels for the study configuration were essentially the same as the baseline aircraft for approach, with a 1.0 to 2.0 EPNL (dB) reduction in takeoff noise and a potential of 2.0 to 3.0 EPNL (dB) reduction for sideline noise.

Impact on Weight and Performance Capability

Multi-element exhaust nozzles were investigated in detail since other features were found to have minor noise reduction results coupled with substantial weight penalties. The installation of exhaust nozzles reduced thrust an estimated 2½ percent and increased specific fuel consumption a similar 2½ percent. The passenger payload decreased because of the 180-pound increase in empty weight. These factors resulted in a significant impact on performance. Rate-of-climb decreased 6 percent. Time to climb to cruise altitude increased 17 percent and cruise speed decreased 2 percent.

Impact on Fuel Efficiency and Cost

Fuel efficiency was adversely affected for the study aircraft. Fuel consumption for the typical mission, as shown in Table 8, increased 5 percent, a significant deterioration in energy efficiency. The acquisition price for the typically equipped baseline aircraft was $1,931,100. The estimated acquisition price for the aircraft equipped with multi-element exhaust nozzles was $1,992,100, 3 percent higher compared to the baseline aircraft.

HELICOPTERS

Representative Aircraft

For the year 1980, helicopters were classified in four groups--light, medium, heavy single, and heavy tandem rotors--with differing missions. For the year 1990 and year 2000 helicopters, however, the missions were kept constant. The reason for maintaining the same mission was to simplify the comparison between noise unconstrained and quiet designs. With the same mission, a comparison of useful load gave the payload penalty incurred by incorporating quieting features in the helicopter design. The effect on mission in the present formulation, therefore, was none. The gross weight of the future helicopters, however, was allowed to increase from the corresponding 1980 gross weights, similiar to the prevailing trends of helicopter growth.

For each of the categories mentioned above, two future helicopter designs were considered. The "Unconstrained Design" corresponded to the future design without any noise contraints, while the "Quiet Design" corresponded to a future design in which noise reduction features were

TABLE 8

GENERAL AVIATION JET AIRCRAFT
REPRESENTATIVE FEATURES

		Typical Design Mission	Typical Operating Mission
Mission Distance	(NM)	1,756	300
Cruise Altitude	(Ft)	41,000	35,000
Maximum Ramp Weight	(Lb)	13,500	13,500
Maximum Takeoff Weight	(Lb)	13,300	13,300
Mission Takeoff Weight	(Lb)	13,300	10,481
Fuel Burned	(Lb)	4,509	1,207
Total Fuel	(Lb)	5,009*	1,707
Reserve Fuel	(Lb)	500	500
Landing Weight	(Lb)	8,991	9,274
Zero Fuel Weight	(Lb)	8,491	8,774
Operator's Empty Weight	(Lb)	7,774	7,774
Payload	(Lb)	717	1,000
Block Time	(Hr)	5.25	1.04
Cruise Speed @ Mid-Cruise Weight	(KTAS)	356	379

*Maximum capacity

incorporated. For both designs, however, the gross weight and mission were maintained to be identical, so that a direct comparison yielded the noise benefits and associated costs.

Technology Features That Reduce Noise

A. Reduced rotor tip speed (both main and tail rotors)
B. Increased rotor solidity or increase number of blades
C. Blade aerodynamic improvements
D. Reducing interference between rotors for tandem rotor helicopters
E. Engine noise reduction through increased rotor/stator stage spacing
F. Inlet and exhaust mufflers
G. Damping materials to gears and shafting
H. Enclosure around gear boxes.

From the above list, the technology features applied to all of the future designs were: (1) reduced rotor tip speed, (2) improved blade aerodynamics, and (3) reduced engine noise. Increased number of blades was not selected for single rotor light and heavy tandem rotor helicopters. Inlet and exhaust mufflers were not considered economically practical for all helicopter designs. Reduced rotor interference was only considered applicable to the heavy tandem rotor.

Acoustic and Economic Analysis

A computer program was used for predicting the external noise of the helicopter. Life Cycle Costs were compared for the baseline, unconstrained, and quiet designs.

Initial investment costs, indirect operating cost, and direct operating costs were calculated for a 15 year life and utilization rate of 500 Hr/Yr. Research and development costs were assessed on the basis of 100 percent payoff for 90 percent R&D expenditure. The initial investment cost included airframe cost, engine cost, initial spares cost and avionics cost. Indirect operating cost consisted of hull insurance cost, while the direct operating cost included costs of fuel and oil, maintenance and spares, and crew. R&D costs were assessed and added to Life Cycle Costs. The cost components and the Life Cycle Costs were therefore based on 15 years, 500 hours per year utilization.

The economics were significantly affected by incorporating quiet design features on future helicopter systems under the constraints of inflexible weight and missions. For 1990 designs, the introduction of noise reduction technology features reduced the useful load by about 3 to 5 percent for a noise reduction of 1.5 to 2.5 dBA. The Life Cycle Costs also went up by 2 to 5 percent. For the year 2000 design, however, the useful load decreased by 10 to 20 percent for a noise reduction of 1.5 to 3.5 dBA in terminal area operations, while the Life Cycle Costs rose as much as 15 to 18 percent.

SECTION 5

DEFINITION OF FLIGHT PATH OPTIONS (VOLUME IV, TASK IV)

Air Carrier Aircraft

Several geometric flight path options for air carrier aircraft were initially considered since they provided acceptable noise relief for each of the representative aircraft. Two options for takeoff flight path and one option for approach flight were finally selected as appropriate for noise relief purposes. Aircraft performance for takeoff options are summarized in Table 9. The flight path option T1 in Table 9 is a deep cutback option and T2 is a maximum climb rate option. Technology improvements were assumed to have no impact on the evaluation of flight path options.

The air carrier aircraft takeoff flight path data were developed as a function of time, power, velocity, distance from start of roll, and altitude to facilitate calculation of noise contours. A computer was used for this complex calculation. In addition to these parameters, fuel flow information was generally provided to the computer in units of lb/hr/engine to produce a better estimation of operating cost.

A common data point for all the represented aircraft on the takeoff profile was the engine thrust level reducing point. The power level was reduced at the end of the flap retraction. The cutback power levels for all represented aircraft are tabulated in Table 10.

The geometry of the air carrier aircraft approach flight path is shown in Figure 1. The path consists of three parts: (1) starting point at 3000 ft altitude 5 N miles away from the intersection of constant altitude flight path and -3^{o} glide slope landing path, (2) constant altitude flight path, and (3) -3^{o} glide slope landing path. Typical data for 2LN aircraft at their approach flight path are also included in Figure 1.

General Aviation Aircraft

The takeoff paths for general aviation aircraft were divided into three categories: (1) single-engined propeller, (2) twin- (or multi-) engined propeller and (3) jet. Takeoff with a lower airspeed and higher climb rate was recommended as the single-engined propeller aircraft option takeoff flight path. This option did not apply to twin-engined propeller aircraft as a result of safety factors arising from an engine failure requiring the pilot to apply full throttle and full propeller RPM on the operating engine in addition to retracting the landing gear and feathering the propeller at a critical period of the flight path. Options were considered in this study which would provide acceptable noise relief only.

TABLE 9

RECOMMENDED DEPARTURE OPTIONS

AIR CARRIER AIRCRAFT

T1

(A) Climb to 1000 feet at V_2 + 10 to 20 at takeoff power.

(B) Pitch over for 750 FPM rate of climb. Accelerate using takeoff power while retracting flaps on normal speed schedule.

(C) After the flaps are retracted, cut back to the thrust so that, subsequent to an engine failure, the one-engine inoperative climb gradient would not be less than 1.2% for two-engined, 1.5% for three-engined and 1.7% for four-engined airplanes. The cutback thrust will be established so that the gradient requirements are met for the maximum takeoff weight condition and at the configuration existing when the cutback is initiated. Accelerate to 1.5 V_S, retracting slats on the normal speed schedule, maintaining 750 FPM rate of climb.

(D) Climb at 1.5 V_S, clean to 3000 feet.

(E) At 3000 feet, change to MCL power and accelerate to 250 KEAS, maintaining 750 FPM rate to climb. If already at 250 KEAS, climb at MCL power.

(F) Climb to 10,000 feet at MCL power at 250 KEAS.

(G) Cruise to 30 nautical miles from brake release at 250 KEAS at 10,000 feet.

T2

(A) Climb to 1000 feet at V_2 + 10 to 20 at takeoff power.

(B) Pitch over for 750 FPM rate of climb. Accelerate, using takeoff power while retracting flaps on normal speed schedule.

(C) After the flaps are retracted, cut back to MCL power. Accelerate to 1.5 V_S, retracting slats on the normal speed schedule, maintaining 750 FPM ratio of climb.

(D) Climb at 1.5 V_S, clean to 3000 feet.

(E) At 3000 feet, accelerate to 250 KEAS, maintaining 750 FPM rate of climb. If already at 250 KEAS, climb at MCL power.

(F) Climb to 10,000 feet at MCL power at 250 KEAS.

(G) Cruise to 30 nautical miles from brake release at 250 KEAS at 10,000 feet.

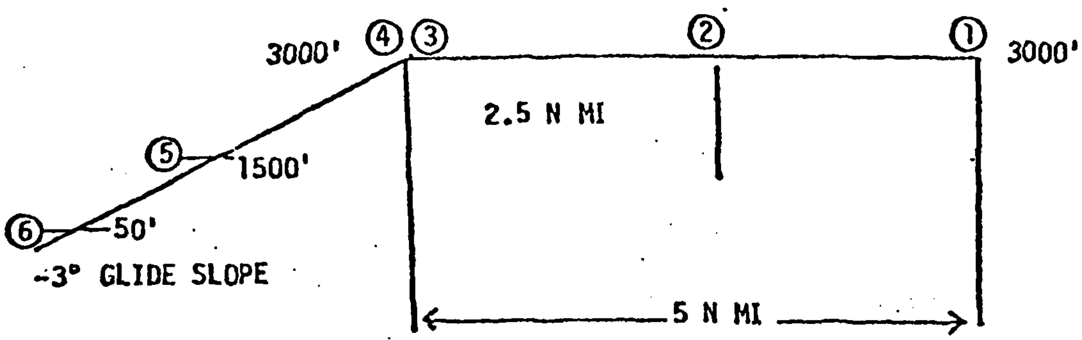
TABLE 10

CUTBACK POWER LEVELS FOR STUDY AIRCRAFT

	AIRCRAFT DESIGNATION	YEAR OF INTRODUCTION	CORRECTED CUTBACK THRUST LEVELS IN POUNDS/ENGINE OPTION T1	OPTION T2
1.	2LN(1)	1980	9,713	9,966
	2LN (RE-ENGINE)	1990	10,329	11,086
2.	3LN	1980	9,509	10,433
	3LN (RE-ENGINE)	1980	9,420	10,750
3.	4LN	1980	8,994	11,235
4.	3HW(1)	1980	23,516	26,128
5.	4HW(1)	1980	27,532	21,264
6.	2LN(2) (REFAN)	1990	12,952	11,103
7.	2HN(1) (NEW)	1990	21,433	24,364
8.	2HW(1) (NEW)	1990	28,181	34,368
9.	2HW(2) (NEW)	1990	31,435	30,070
10.	3HW(2) (STR)	1990	23,529	29,037
11.	4HW(2) (STR)	1990	25,805	27,500
12.	2HN(2) (STR)	2000	13,858	15,107
13.	3HW(3) (STR/ADV)	2000	23,529	29,037
14.	4HW(3) (LARGE)	2000	31,496	36,898

FIGURE 1. APPROACH FLIGHT PATHS

AIRCRAFT #1
2LN (1)



1	START OF APPROACH FLIGHT PATH (TIME = 0 SECONDS)
1, 2 & 3	APPROACH FLAP SETTING
5, 4 & 6	ALTERNATE LANDING FLAP SETTING

TYPICAL TECHNICAL CHARACTERISTICS FOR 2LN AIRCRAFT
IN THEIR APPROACH FLIGHT PATH

POINT	1	2	3	4	5	6
FLAP (DEGREES)	5	5	5	40	40	40
ALTITUDE (FT)	3000	3000	3000	3000	1500	50
VELOCITY (KEAS)	146.9	146.9	146.9	133.5	133.5	133.5
Fn/δ (LB)	4545	4545	4545	4504	4274	4962
W_f (LB/HR/ENG)	3058	3058	3058	2979	3026	3078
$N1/\sqrt{\theta_T}$ (RPM)	5965	5965	5930	5930	5820	5720
DISTANCE TO TOUCHDOWN (FT)	87578	72410	57243	57243	28622	954
TIME (SECONDS)	0	57.6	115.2	115.2	236.1	355.5
GEAR	UP	UP	UP	DOWN	DOWN	DOWN

Two different takeoff path options were recommended as producing noise reduction for twin-engined propeller aircraft: (1) the path with increasing takeoff power, climb rate and a reducing airspeed, or (2) a reducing propeller RPM at normal power level and increasing manifold pressure. Information for calculating ground noise exposure for a normal and optional propeller aircraft takeoff path is listed in Table 11.

Procedures for general aviation aircraft approach flight paths followed the same sequences as for their takeoff flight paths. For a single-engined propeller, the optional approach flight path differed from the normal flight path by using a tighter pattern and delaying the use of flaps to reduce the power requirement, producing a lower noise level. Both normal and optional approach flight paths are shown in Figure 2 and Table 12.

An optional approach flight path for a twin-engined propeller with a higher manifold pressure and lower propeller RPM was recommended to reduce noise landing. Both normal and optional approach flight paths followed the same landing profile with a 3 degree approach angle before the landing gear was extended at 50 ft above ground level. This optional approach flight path, though, should not be used when a go-around condition occurs. The normal approach flight path has a higher propeller RPM, providing better handling than the option. Information for noise level calculations for both paths is listed in Table 13.

According to the National Business Aircraft Association's (NBAA's) Noise Abatement Procedures, the optional general aviation jet takeoff flight path requires jets to use takeoff power to 1500 ft altitude, then reduce power to sustain a 1000 FPM climb rate until the aircraft reaches 3000 ft above field level (AFL). After reaching 3000 ft. AFL, the flight path resumes a normal climb schedule. The takeoff flight path for normal and optional paths are summarized in Figures 3 and 4 and Tables 14 and 15.

For jet-powered general aviation aircraft, a 3° descending path from 2500 ft AFL with lower engine power than for the normal path was recommended as an optional approach flight path. Based on the results of this study, considering options which would provide acceptable noise relief only, however, the low engine power used in the initial approach segment in the flight path option might not provide enough anti-icing capacity for the the aircraft. Details of normal and optional jet approach flight paths are provided in Figures 5 and 6 and Tables 16 and 17.

Helicopters

There were an infinite number of available flight path options for helicopters since they were not constrained to follow any specified path. Helicopter noise impact to residential areas can be minimized by either controlling the rotor characteristics, which significantly contribute to noise (such as, directivity, tip speed, blade vortex interaction, forward speed), or choosing flight paths not adjacent to residential areas. For a flight path near airports or heliports, a faster descent and takeoff path were considered as an optional path. A 1.8 dB(A) improvement at ground level occurred when a helicopter increased its climb rate from 600 FPM to 900 FPM. The same phenomenon was found for the landing path. A 1.9 dB(A)

TABLE 11

TAKEOFF FLIGHT PATH OPTIONS
GENERAL AVIATION FIXED-WING PROPELLER AIRCRAFT

	SINGLE ENGINE	
	NORMAL	OPTION #1
HORSEPOWER	150	137
PROPELLER RPM	2490	2410
AIRSPEED, KIAS	85	73
RATE OF CLIMB, FPM	500	755

	TWIN ENGINE		
	NORMAL	OPTION #1	OPTION #2
% POWER	75	100	75
HORSEPOWER, each	232	310	232
MANIFOLD PRESSURE, inches Hg	30	38	34
PROPELLER RPM	2450	2700	2200
AIRSPEED, KIAS	120	108	120
RATE OF CLIMB, FPM	1240	1650	1240

NOTES: 1. Data is for sea level, standard day conditions.

2. Takeoff is with 100 percent power. Data in tables is for the climb after takeoff.

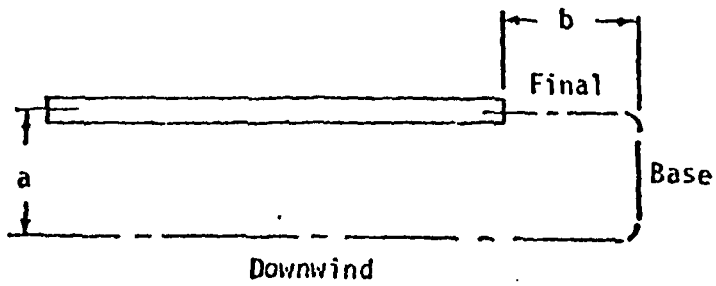


FIGURE 2. Approach Flight Path,
Fixed-Wing Single Engine Propeller Aircraft

TABLE 12

APPROACH FLIGHT PATH
FIXED-WING SINGLE ENGINE PROPELLER AIRCRAFT

	Normal	Option #1
Downwind:		
"a" ft	4000	3000
Altitude, ft	800	800
Wing Flap, degrees	10	0
Airspeed, knots	70	70
RPM	1750	1700
Horsepower	53	51
Base:		
Altitude, ft	800 to 400	800 to 400
Wing Flap, degrees	20	0
Airspeed, knots	65	65
RPM	1600	1500
Horsepower	48	45
Final:		
"b", ft	4000	3000
Altitude, ft	400 to 0	400 to 0
Wing Flap, degrees	40	40
Airspeed, knots	60	60
RPM	1650	1650
Horsepower	50	50

TABLE 13

APPROACH FLIGHT PATH

FIXED-WING TWIN ENGINE PROPELLER AIRCRAFT

	TWIN ENGINE	
	NORMAL	OPTION #1
HORSEPOWER, each	120	120
MANIFOLD PRESSURE, inches HG	17	18
PROPELLER RPM	2700	2450
AIRSPEED, KIAS	100	100
APPROACH ANGLE, degrees	3	3

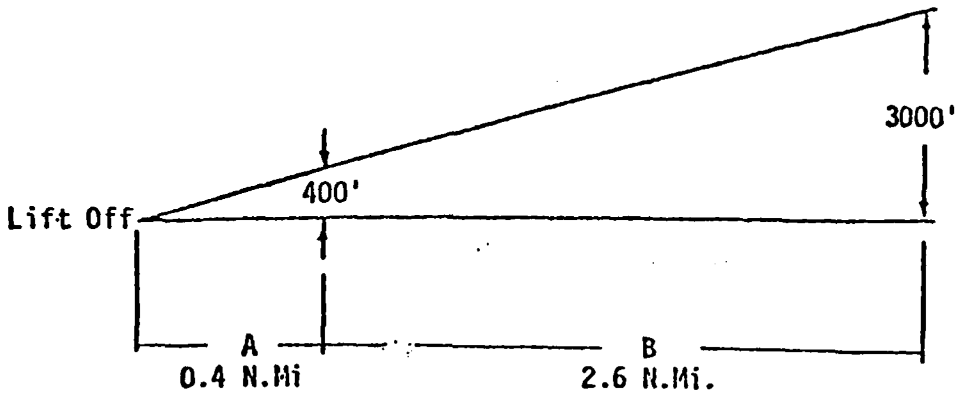


FIGURE 3

Normal Takeoff Flight Path

TABLE 14

NORMAL TAKEOFF FLIGHT PATH
GENERAL AVIATION JET AIRCRAFT

	Segment A	Segment B
Wing Flaps	Takeoff	Up
SPEED (knots)	114 to 180	180
Fan Speed (%)	98.5	98.5
RPM	15,660	15,660
Total Thrust	3,950	3,850

Notes: 1. Takeoff at maximum takeoff weight

2. Above 300 feet resume normal climb schedule

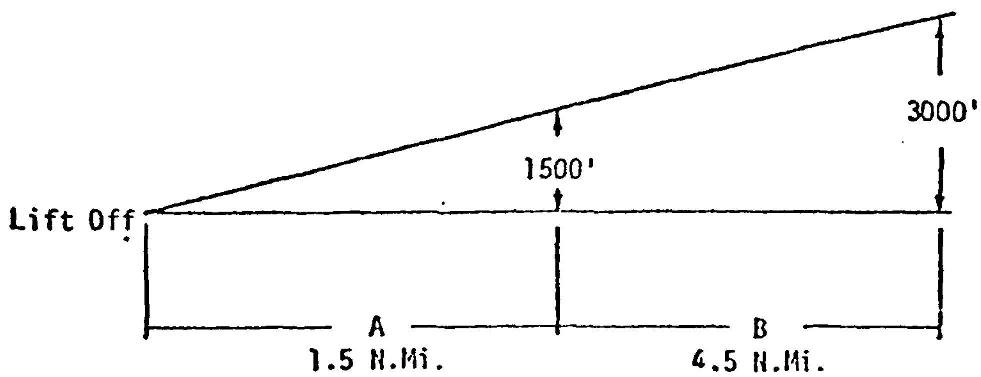


FIGURE 4

Takeoff Flight Path Option

TABLE 15

TAKEOFF FLIGHT PATH OPTION
GENERAL AVIATION JET AIRCRAFT

		Segment A	Segment B
Wing Flaps		Takeoff	Up
Speed (knots)		124	180
Fan Speed	(%)	98.5	82
	(RPM)	15,660	13,000
Total Thurst	(lb)	4,000	1,900

Notes:
1. Takeoff at maximum takeoff wieght
2. Power in segment B is adjusted to give approximately 1000 FPM rate of climb
3. Above 3000 feet resume normal climb schedule

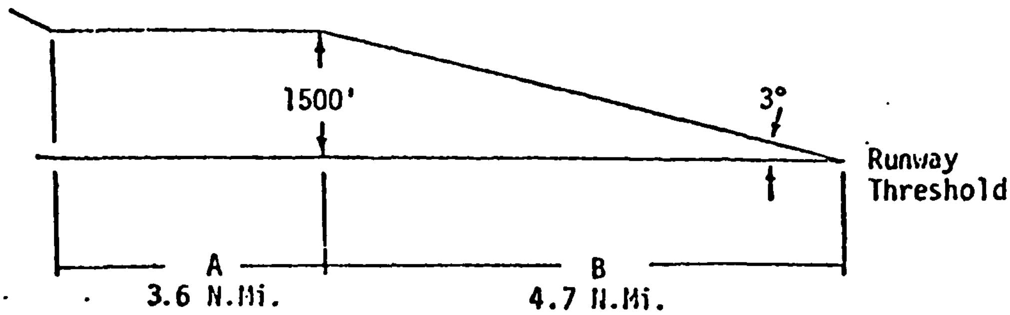


FIGURE 5

Normal Approach Flight Path

TABLE 16

NORMAL APPROACH FLIGHT PATH
GENERAL AVIATION JET AIRCRAFT

		Segment A	Segment B
Landing Gear		Up	Down
Wing Flaps		Approach	Landing
Speed (knots)		175	115
Fan Speed	(%)	65	62
	(RPM)	10,335	9,860
Total Thurst (lb)		1,250	1,300

Notes: 1. Data are for typical landing weight

2. Airspeed decreases in segment B to 95 knots when 50 feet above runway threshold at which point thrust is reduced to idle

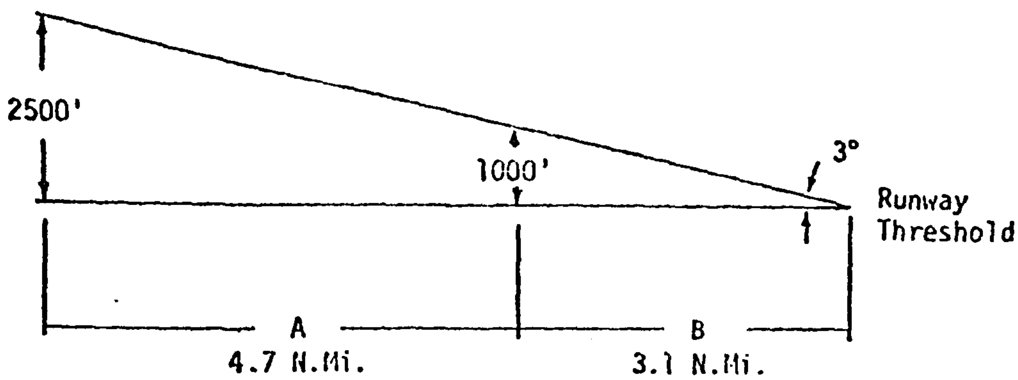


FIGURE 6

Approach Flight Path Option

TABLE 17

APPROACH FLIGHT PATH OPTION
GENERAL AVIATION JET AIRCRAFT

		Segment A	Segment B
Landing Gear		Up	Down
Wing Flaps		Approach	Landing
Speed (knots)		115	115
Fan Speed	(%)	42	62
	(RPM)	6680	9860
Total Thurst	(lb)	400	1300

Notes:
1. Data are for typical landing weight
2. Low power for segment A not sufficient for airplane anti-ice
3. Airspeed decreases in segment B to 95 knots when 50 feet above runway threshold at which point thrust is reduced to idle

improvement occurred when the helicopter increased its descent rate from 639 FPM to 1072 FPM. Normal and optional helicopter takeoff and landing paths are illustrated in Figures 7 and 8. All the helicopters (light, medium, and heavy) would produce approximately the same noise reduction benefit.

Navigation and Avionics Equipment

Navigation and avionics equipment is required to effectively implement optional flight path procedures and to avoid unnecessary aircraft delays. Airport activity levels will increase from 1980 to 2000. Even now, some airports have a critical delay problem. Limited efforts, including the construction of extra runways and the improvement of the ATC system, are being attempted to try to improve the delay condition. In addition, a number of new ATC ground systems will be installed at selected airports to increase runway capacity.

The requirements for additional aircraft avionics needed for implementation of the proposed noise reduction flight path options at the airports by the year 2000 can be met with a three-dimensional area navigation system (3D R-NAV) including a software addition to the navigation computer. The additional software will consist of an algorithm defining the aircraft vertical descent profile and will present to the integrated navigation, guidance, control and display systems the noise reduction flight path to be used. These pieces of equipment are currently being installed as part of the flight deck displays and controls for use with the avionics that interface with ground-based navaids and the air traffic control system. Present cost of a 3D R-NAV system including flight profile software amounts to $530,000 per shipset. This price includes $215,000 for three Inertial Navigation Systems for overwater flights and 3D R-NAV for domestic operation amounting to $315,000 per shipset.

TAKEOFF FLIGHT PATH OPTION

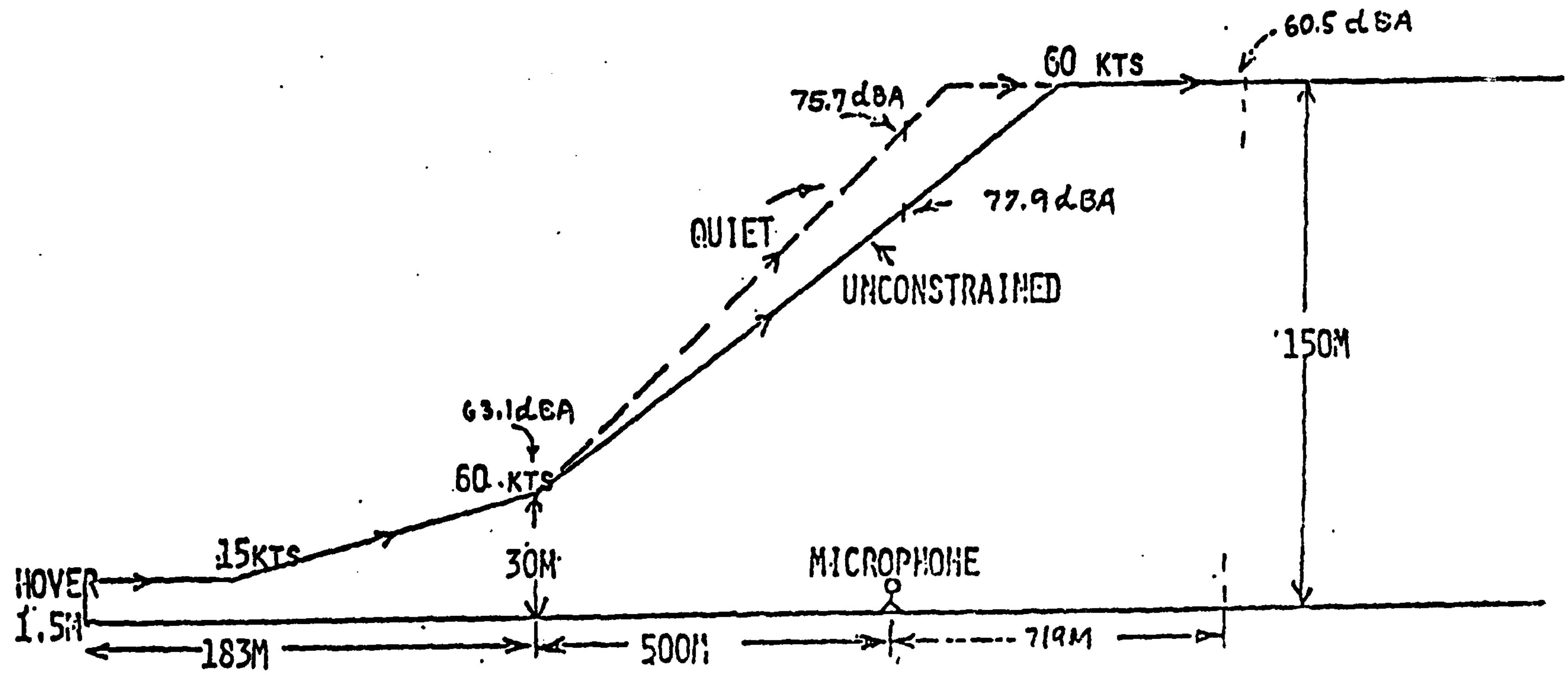


FIGURE 7

LANDING FLIGHT PATH OPTION

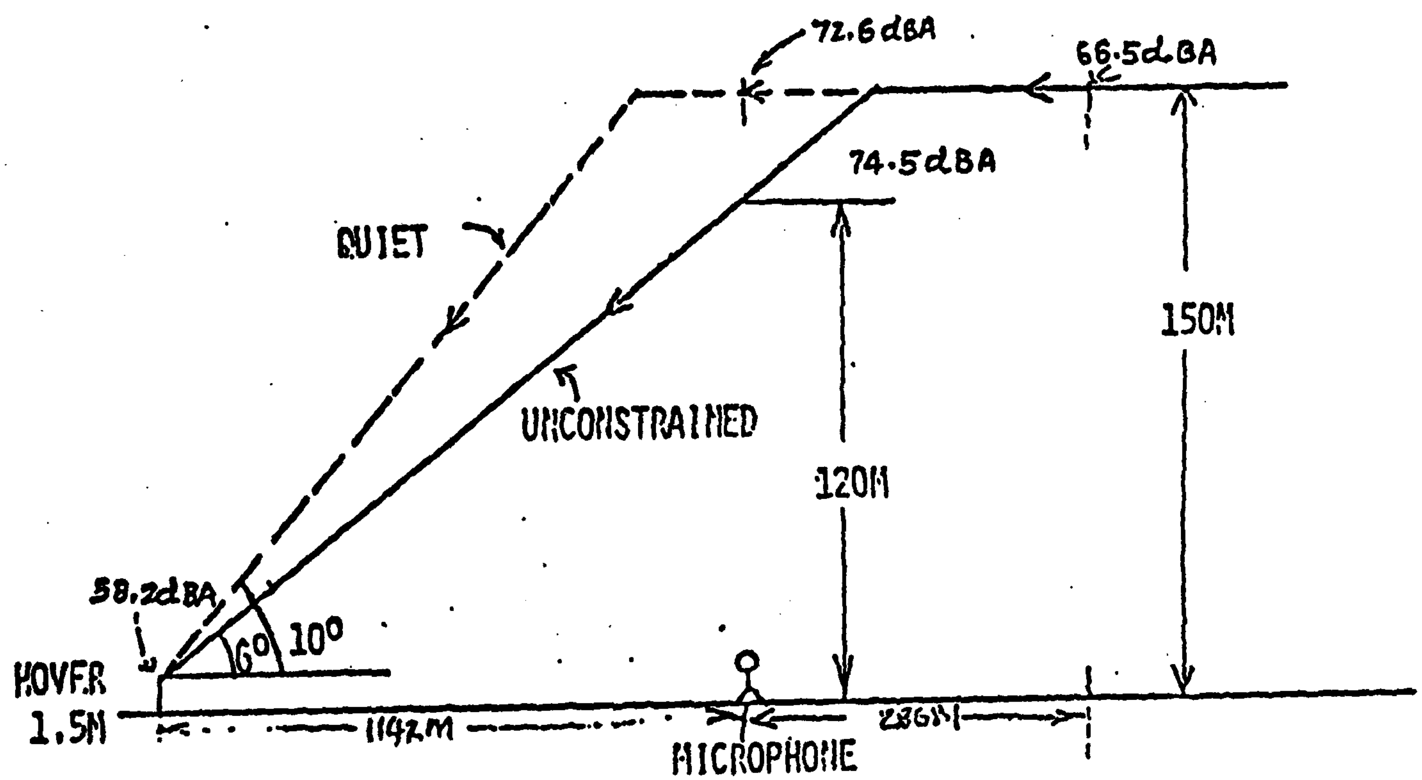


FIGURE 8

SECTION 6

LAND USE OPTIONS

(VOLUME V, TASK V)

According to the Aviation Noise Abatement Policy (ANAP) statement issued in 1976, the Department of Transportation (DOT) estimated that six to seven million Americans are significantly annoyed by aircraft noise. This problem could be diminished, as directed in the ANAP statement, by reducing aircraft noise at its source; promoting safe operational procedures that abate the impact of noise on populated areas; and promoting efforts to attain compatible land use in areas adjacent to airports.

For purposes of this study, the overall airport system in the U.S. was divided into four classes to simplify the cost-benefit analysis at the national level. These four classes are shown in Table 18. Several airports were then selected to represent all of the airports in that particular class. A total of 14 sample airports were selected (see Table 19). Sample "cells" were randomly selected from within the Noise Exposure Forecast (NEF) 30 contours for each airport area to represent the noise-impacted population in the vicinity of that airport. NEF 30 contours were used for each of the sample airports and reflected the lower criterion level of noise impact (L_{dn} 65) considered for this study. "Cells" were defined to be 1000-foot squares (10^6 square feet in area). The samples of "cells" for each airport class were then considered representative of all airports in that class.

In addition, 12 land use options were examined (Table 20), based on a review of the literature, to determine compliance with the requirements set out for including land use options in the unit cost analysis. These requirements were that the selected land use options should be applicable nationwide, be amenable to public adminstration, provide benefits in terms of direct reduction of noise exposure, and result in costs and benefits that could be readily quantifiable for use in the cost-benefit analysis.

Examination of the preliminary listing of land use options (Table 20) showed an immediate conflict between these requirements and some of the options listed. For example, those options which gave only economic or informational benefits were excluded from further consideration. These are, from Table 20,

- Aviation easements
- Tax abatement
- Public disclosure/environmental impact reports
- Purchase assurance.

TABLE 18

AIRPORT CLASSES

Class	Average Number of Daily Scheduled Arrivals
1	More than 500
2	250 to 500
3	100 to 250
4	Less than 100

TABLE 19

SUMMARY OF AIRPORT SAMPLE SELECTED FOR ANALYSIS

Class	AIRPORT	Arrivals/Day
1	ORD (Chicago O'Hare)	967
	ATL (Atlanta)	637
	LAX (Los Angeles International)	594
2	JFK (New York City Kennedy)	410
	BOS (Boston Logan)	409
	DCA (Washington National)	346
	STL (St. Louis Lambert)	292
3	DTW (Detroit Metropolitan)	248
	TPA (Tampa, FL)	192
	SAN (San Diego Lindbergh)	122
	SJC (San Jose Municipal)	100
4	SNA (Orange Co., CA)	63
	RNO (Reno, NV)	47
	DLH (Duluth, MN)	14

TABLE 20

PRELIMINARY LIST OF AIRPORT LAND USE OPTIONS

TO BE CONSIDERED IN UNIT COST ANALYSIS

Aviation Easements

Building Codes

Deed Restrictions

Noise Charges

Preemption of Vacant Land (Land Banking)

Public Disclosure/Environmental Impact Reports

Purchase Assurance

Relocation (Condemnation of Developed Property/Redevelopment)

Sound Insulation

Tax Abatement

Transfer of Development Rights

Zoning

Additionally, options of a private nature such as deed restrictions were omitted. The remaining seven options were examined in further detail to determine their compliance with the study's requirements. The pros and cons of each of these land use options is summarized in Table 21.

Of the seven options, the review indicated that all but noise charges and transfer of development rights were viable from the viewpoints of legal, social, and institutional and administrative issues, and were considered as providing benefits in alleviating the effects of aircraft noise exposure. The rationale used for the final selection of land use options for the cost-benefit analysis can be explained by considering two separate characteristics of the options, according to their applicability to

(a) dwellings which already exist (or are expected to exist) during the year 1980, and

(b) dwellings which might be constructed in subsequent years.

Table 22 shows this separation of the options.

The costs and benefits of the options in both of the categories in Table 22 were examined in order to determine their compliance with the requirement that both the costs and and benefits of selected options be readily quantifiable. The costs and benefits of the Options Applicable to Existing Dwellings met this requirement and were therefore examined in the cost-benefit trade-off. However, in order to quantify the cost and benefits of the Options Applicable to Future Developments, an extensive survey of the amount of land available for development at each of the sample airports would have been necessary. Thus, the costs and benefits of these options were not easily quantifiable, and such an extensive survey as would be required to obtain this data was beyond the scope of the study. This eliminated the three options - Preemption of Vacant Land, Zoning, and Building Codes (for new dwellings) - from further consideration for inclusion in the cost-benefit analysis of land use options.

The options selected for unit cost analysis and application in the cost-benefit analysis were:

- o Relocation, including condemnation of developed property and redevelopment,
- o Sound Insulation of Existing Buildings, and
- o National Changes to Building Codes.

RELOCATION

Condemnation of Developed Property

Condemnation of developed property requires a governmental exercise of the power of eminent domain over improved land, through the taking of private property for public use and benefit, upon the payment of just compensation.

TABLE 21

PROS AND CONS OF AIRPORT LAND USE OPTIONS

Options	Pros	Cons
Building Codes	o Approximately 98% of all cities utilize building codes. o Noise benefits can be readily quantified. o Required construction techiques have been successfully applied.	o Long-term, future benefits only - not retroactive: cannot be applied to existing buildings (unless the existing building is demolished and rebuilt). o Requires enforcement and administration mecanism.
Sound Insulation	o Noise benefits can be readily quantified. o Required construction techniques have been successfully applied. o Benefits accrue as soon as option is implemented.	o Voluntary implementation if not funded by government.
Condemnation of Developed Property (and Relocation of Affected Residents)	o Achieves compatibility between airport and surrounding community. o Noise benefits can be readily quantified.	o High acquisition cost. o Reduced property tax base. o Depletion of single-family housing. o Disruption of community identify. o Absorption rate of land for compatible reuse can be low. o Relocation is difficult and socially disruptive.
Redevelopment	o Achieves compatibility between airport and surrounding community. o Increased long-term tax base established with added commercial or	o Depletion of single-family housing. o High acquisition cost. o Windfall profits by redevelopers.

(continued)

TABLE 21 (continued)

Options	Pros	Cons
	industrial land reuse. o Absorption rate of land for compatible reuse can be high for small land areas.	o Relocation is difficult and socially disruptive. o Absorption rate of land for compatible reuse of large land areas affected by airport noise is low.
Preemption of Vacant Land (Land Banking)	o Ensures future compatibility between airport and land which is currently vacant. o Since land is vacant, demolition of buildings is not required. o Retains community identity, relocation not required.	o Reduced property tax base. o Absorption rate of land for compatible reuse can be low. o High acquisition cost. o Long-term, future benefits only.
Noise Charges	o Aircraft pays pollution charge which compensates damaged parties for noise emissions.	o In conflict with airline/airport contracts and many international civil aviation agreements. o Requires enforcement and administration mechanism. o Largely untested in practice.
Transfer of Development Rights	o Utilizes private funds to achieve airport-compatible land uses.	o May constitute an invalid exercise of the police power. o Requires enforcement and administration mechanism. o Long-term benefits only. o Largely untested in practice.

(continued)

TABLE 21 (continued)

Options	Pros	Cons
Zoning	o Separates incompatible land uses.	o Long-term future benefits only (not retroactive: cannot be applied to existing buildings). o Reduced property tax base if rezoned to less intensive uses. o Influenced by local political forces; as a result, variances are frequently granted. o Requires area-wide planning when more than one municipality is impacted.

TABLE 22

LAND USE OPTIONS CATEGORIZED ACCORDING TO
APPLICABILITY TO EXISTING AND FUTURE RESIDENTIAL DEVELOPMENTS

Options Applicable to Existing Dwellings	Options Applicable to Future Developments
o Relocation (Condemnation of Developed Property/Redevelopment	o (Redevelopment)
	o Preemption of Vacant Land
o Sound Insulation (Remedial)	o Zoning
o Building Codes (for replacement dwellings)	o Building Codes (for new dwellings)

Condemnation of developed property can result in compatibility between the airport and its surrounding community. Although it can be expensive and potentially disruptive, it results in a direct reduction in the number of people exposed to a given noise level.

Redevelopment

Redevelopment is really an extension of the Condemnation of Developed Property option. Redevelopment has been proven to be a very difficult and expensive alternative. In most cases, the potential resale value of the land is less than the cost of residential land when the value of houses is considered. Thus, redevelopment requires large subsidies in most cases. Redevelopment has been found to be justified, however, in selected small, heavily impacted areas. If the airport authority maintains control over the redevelopment sites, redevelopment can provide a permanent solution for the specific area. Thus, redevelopment, as an extension of the option of condemnation of developed property, can be considered an effective solution to airport noise.

The unit-cost analysis of the Relocation option provided the cost per cell incurred through the acquisition of residential property within the cell, relocation of the affected residents, and redevelopment of the acquired land for industrial and commercial reuse. In order to obtain the most up-to-date cost information, local residential and industrial property values were obtained from realtors in each airport area. Methodologies were developed, in compliance with current legislative guidelines on relocation and land acquisition, to calculate cost data based on current property values, number of housing units per cell, and acquisition, relocation and redevelopment costs incurred by the purchasing agent.

An example of the relocation costs for the Atlanta International Airport is shown in Table 23. Based on this data, a $136,666 average relocation cost per acre for all 105 cells surrounding Atlanta International Airport was determined. The value is within 1 percent of relocation costs per acre projected by the Department of Housing and Urban Development in a current program to relocate 311 families from under the flight path of the Atlanta International Airport.

SOUND INSULATION OF EXISTING DWELLINGS

The application of sound insulation to existing buildings can often achieve improved attenuation between exterior and interior noise levels. Several studies have indicated that a substantial benefit can be obtained by a remedial insulation program.

Unit costs for the Sound Insulation of Existing Dwellings were estimated per 1000 sq ft of floor area for three levels of insulation improvement - by 5, 10, and 15 dB(A). Estimates were based on results from three previous sound insulation study programs which were revised and updated for use in this program. Table 24 provides a summary of the esti-

TABLE 23 RELOCATION COSTS FOR CELLS IN THE ATLANTA INTERNATIONAL AIRPORT AREA

Cell Coordinates (ft)		Cell Number	Cell Population	Relocation Costs (x $1000)	Sq Ft Housing x 1000
8500.	-23500.	1	266	3363.	122.2
21500.	-29500.	2	49	381.	15.0
20500.	-29500.	3	13	222.	8.7
21500.	-28500.	5	183	2095.	82.5
22000.	-27500.	7	92	794.	31.2
21500.	-27500	8	22	222.	8.7
20500.	-26500.	9	364	3764.	147.5
15500.	-26500.	10	86	1489	56.0
18500.	-25500.	11	391	3700.	139.2
9500.	-22500.	12	377	4221.	153.4
8500.	-22500.	13	288	3792.	137.8
7500.	-21500.	14	333	4186.	152.1
12500.	-20500.	15	96	1560.	56.0
11500.	-20500.	16	375	5265.	189.0
9500.	-18500.	17	160	1950.	70.0
13500.	-17500.	18	41	661.	22.0
21500.	-16500.	19	383	3849.	136.8
19500.	-16500.	20	271	2667.	94.8
13500.	-16500.	21	185	2942.	97.9
12500.	-16500.	22	38	463.	15.4
20500.	-15500.	23	147	1620.	57.6
14500.	-15500.	24	221	2578.	85.8
13500.	-15500.	25	158	1884.	62.7
14500.	-14500.	26	181	1950.	64.9
12500.	-14500.	27	292	4033.	134.2
11500.	-14500.	28	145	1851.	61.6
36500.	-13500.	29	63	1098.	41.3
19500.	-13500.	31	207	2161.	76.8

mated 1979 costs of sound insulation for 5, 10, and 15 dB(A) noise level improvements. The three studies gave widely varying estimates of the cost of sound insulation, when factored to a 1979 dollar base. Without any concrete evidence to substantiate these or any other cost estimates for the sound insulation of existing dwellings, the average costs per 1000 sq. ft. of floor space shown in Table 24 were used in the cost-benefit analysis.

BUILDING CODES

Building Codes are defined as local or state-adopted regulations, enforceable by police powers and governed by health, safety and welfare considerations. They control the design, construction, alteration, repair, quality of material used, and related factors of any building within the jurisdiction of the enacting government unit. Building Codes relating to sound insulation are designed to promote a satisfactory interior noise environment conducive to the comfort, health and privacy of occupants. They are applied to new construction and are not applicable to buildings constructed prior to the formulation of the codes.

The land use option of applying Building Codes to housing in noise-impacted areas was directed toward the sound insulation of residential structures, which would replace structures existing in 1980. Unit costs were therefore based on the estimated cost of applying sound insulation at the design stage rather than the remedial stage, as in the Sound Insulation option. These costs were estimated, for each of the three levels of improvement, as a percentage of the estimated costs of remedial sound insulation. Unit costs were provided in dollars per 1000 sq ft of floor area. The resulting unit costs were:

Level of Improvement for New Housing dB(A)	Cost per 1000 sq.ft of Floor Area ($)
5	3,900
10	6,400
15	10,800

The resultant unit cost data developed for each land use option was subsequently used in the final cost-benefit analysis to determine the optimal aircraft noise abatement measures, and combination of measures, for reducing aircraft noise exposure nationwide.

TABLE 24

COSTS OF SOUND INSULATION, UPDATED TO JULY 1979, BY THE HOMEOWNERS COST INDEX (HCI) RATIO

Year	Unit	1979 Cost($)/1000 sq. ft. Floor Area		
		5 dB(A)	10 dB(A)	15 dB(A)
1966*	PNdB	2,605	7,374	17,479
1975*	dB(A)	3,718	10,610	19,264
1973**	dB(A)	9,860	18,645	22,948
Average	-	5,394	12,210	19,897

*Aircraft Noise Abatement Studies

**Road Traffic Noise Abatement Studies

PNdB: Maximum Perceived Noise Level

dB(A): A-Weighted Noise Level

SECTION 7

COST-BENEFIT ANALYSIS
(VOLUME VI, TASK VI)

The costs and noise impact benefits associated with aircraft technology changes, modified operational procedures for departure flights, and land use options applicable to residential areas in the airport environment were compared. The methodology involved an application of each of these options, including baseline cases, to 14 separate sample airports representing the nation's network airport (Table 19). Benefits were assessed by evaluating the reduction in Noise Impact Index (NII) over a wide demographic sample representing the noise impacted residential population. The year 1980 has been used as the baseline year representing the current state of noise impact, aircraft technology, aircraft fleet mix, and operating procedures. Future planning years (1990 and 2000) have been used as a basis for comparison of the benefits to be accrued by various "Countermeasures" applied in isolation and in conjunction with each other. These countermeasures included:

- o Source noise reductions obtainable by selective modification or replacement of existing and/or predicted future aircraft.
- o Operational ("flight path") methods for takeoff procedures to alleviate noise impact.
- o Land use options which would reduce the aggregate impact of noise either by reducing the number of people affected or by reducing their exposure to aircraft noise.

A summary of all potential countermeasures considered in this study is presented in Table 25. Except for takeoff procedure modifications, no countermeasures were applied to planning year 1980 since there was no lead time to effect changes.

The application of the countermeasures to the 14 sample airports (and airport classes) was accomplished by means of the following basic steps:

- o Each airport area was subjected to a spatial sampling procedure to provide a representative sample of populated land parcels (cells). A total of 929 cells were sampled for all four airport classes.
- o The geographic location of each cell was uniquely identified in order that its noise impact due to aircraft operations could be calculated.

TABLE 25

POTENTIAL COUNTERMEASURES

Identifier*	Description	Affected Source	Planning Year In Which Effective
TA	Refan 2LN1 Fleet	2LN1	1990
TB	Refan 3LN1 Fleet	3LN1	1990
TC	Refan 2LN1 Fleet	2LN1	2000
TD	Refan 3LN1 Fleet	3LN1	2000
TE	Replace 2LN1 Fleet by 2LN2	2LN1	1990
TF	Replace 3LN1 Fleet by 2LN2	3LN1	1990
TG	Replace 2LN1 Fleet by 2LN2	2LN1	2000
TH	Replace 3LN1 Fleet by 2LN2	3LN1	2000
TI	Replace 4LN1 Fleet by 3HW1 with LDN	4LN1	1990
TJ	Replace 4LN1 Fleet by 3HW2 with LDN	4LN1	1990
TK	Replace 4LN1 Fleet by 3HW3 with LDN	4LN1	2000
TL	Retrofit 3HW1 with LDN	3HW1	1990
TM	Retrofit 3HW1 with LDN	3HW1	2000
TN	Retrofit 4HW1 with LDN	4HW1	1990
TO	Retrofit 4HW1 with LDN	4HW1	2000
TP	Retrofit 2HN1 with LDN	2HN1	2000
TS	Build 2HW2 with LDN	2HW2	1990
TT	Build 2HW2 with LDN in 2000 but not in 1990	2HW2	2000
TU	Build 2HW2 with LDN in 2000 and in 1990	2HW2	2000
FA	All aircraft use deep cutback procedure instead of max climb cutback	All	1980
FB	Same	All	1990
FC	Same	All	2000
LA	Increase building sound insulation	All	1990
LB	Same	All	2000
LC	Relocate population	All	1990
LD	Same	All	2000

* T = technology option
  F = flight path option
  L = land use option

- o Demographic and land use characteristics were compiled for each cell. These characteristics include 1980 population projections, number of housing units, total square footage area of floor space, total 1980 value of residential property and the potential cost of relocating all residents in the cell to a nonimpacted region.

- o The noise impact index (NII), an estimate of the percentage of "highly annoyed" people in the airport vicinity, at each cell was calculated on the basis of the aircraft operations. These operations were obtained separately for the planning years. The operations for each planning year included separate combinations of flight path options and aircraft noise reduction technology.

The above descriptions provided the bases for the procedural approach used in the analysis. By means of these basic steps, which essentially provided the modeling and quantification of costs and benefits of each countermeasure group (i.e., source noise reductions, flight path and land use options), the tradeoff and optimization analysis was performed using the following numerical methods.

For the cost-benefit analysis, an existing computerized method, developed by Wyle Laboratories, called Noizop was used. The basic task performed by Noizop was, for a specified distribution of expenditures (the hypothetical budget), to apply the countermeasures at each cell, noting the number of people no longer adversely affected by noise, and computing a new (reduced) noise impact index (NII). This task was performed a large number of times during any one execution of Noizop as it searched for the distribution of expenditures which gave the greatest NII reduction for a given budget.

Table 26 gives the budgets for the Noizop analysis. During an initial analysis it was found that countermeasures TE and TG (see Table 25), involving replacement of 2LN1 aircraft, were not implemented by the program because they were not sufficiently cost effective compared with other options. New budgets were therefore established to exclude these countermeasures, as shown in Table 27. Overall, the best scenarios were those that resulted in the lowest NII for a given budget, after examining the effects of pooling countermeasures. A cost-benefit ratio was defined as follows:

$$\frac{\text{Percent of Maximum Budget Spent}}{\text{Noise Impact Index Reduction in Percent}}$$

which is a nondimensional number rating the quality of a countermeasure implementation scenario; the lower the number the more attractive the tradeoff analysis.

Each of the land use options was associated with a cost which, in the case of relocation, was equal to the relocation costs input for each cell and, in the case of insulation, equalled the cost of insulation per unit

TABLE 26

BUDGETS FOR NOIZOP ANALYSIS (MILLIONS OF $)

Airport Class[1]	Planning Year 1990	Planning Year 2000
1	1,200	1,800
2	2,000	3,700
3	2,000	2,600
4	4,200	7,300
	9,400	15,500

[1]See Tables 18 and 19

TABLE 27

BUDGETS FOR NOIZOP ANALYSIS WITHOUT COUNTERMEASURES TE AND TG (MILLIONS OF $)

Airport Class[1]	Planning Year 1990	Planning Year 2000
1	446	1,215
2	747	2,033
3	557	1,960
4	1,075	4,105
	2,825	9,313

[1]See Tables 18 and 19

area times the cell's area of inhabited floor space. Each of those options was also associated with a benefit which was equal to the number of people removed from the list of those who were "highly annoyed." This benefit was equal to te cell's "highly annoyed" population in the case of relocation and, in the case of the insulation options, was calculated according to the additional insulation's effect on interior noise levels. For each cell, Noizop determined a cost/benefit ratio for each available option, and drew up a list of options ordered or sorted according to that ratio. The available land use options budget was then allocated first to those options with the best (i.e., lowest) cost/benefit ratios, until the budget was exhausted. In this way, a mixture of recommended land use actions resulted where each cell was treated individually according to its idiosyncrasies of noise exposure and people count. Noizop then summarized the expenditures on each of the land use options.

When all countermeasures were allowed simultaneously in any combination, data such as that presented in Tables 28 and 29 resulted. Each line corresponds to a scenario. In these tables, the first column indicates that all airport classes in Tables 18 and 19 are being considered. The second column gives the amount of hypothetical funds (in 1980 constant dollars) expended for any particular combination of countermeasures (see Table 27). The third column contains the Noise Impact Index in percent (an estimate of the percentage of "highly annoyed" people in airport vicinities). In the upper left corner, each table shows a "baseline" NII; this baseline refers to the case where none of the countermeasures mentioned on the table are implemented, i.e., with just all "free" countermeasures. The columns under the heading "Countermeasures (Percent of Budget)" list the expenditures on each countermeasure in terms of percent of the maximum budget which is also given in the upper left corner of the table. The next to last column records a cost-benefit ratio previously defined. In the last column, the rank indicates the sequence in which countermeasures scenarios should be implemented if only partial budgets are available. For example, if severe budget restrictions were imposed, one might be content to choose the scenario with rank 1, with a cost-benefit ratio of 116 in Table 28. The ranking of scenarios was not only done by the cost benefit ratio, but it was also required that any countermeasures included in one scenario must be kept in subsequently ranked scenarios. The rank in Tables 28 and 29 therefore indicates in which sequence countermeasures should be implemented with increasing budgets. Table 30 summarizes the noise impact ranking of aircraft in each of the planning years and the results are discussed below.

COUNTERMEASURE IMPLEMENTATION AS RECOMMENDED BY THE TRADEOFF ANALYSIS

"Free" Countermeasures

This section formulates recommended actions on the basis of the analysis performed. Several assumptions and simplifications were needed to reduce a highly complex set of variables to a manageable data base. The following is a list of the most important assumptions and simplifications made at the time of this study in 1979:

- The national air carrier fleet was broken down into 14 categories, each represented by one "representative" aircraft (Table 4).

TABLE 28

NOIZOP RESULTS FOR CLASS All AIRPORTS, PLANNING YEAR 1990, ALL COUNTERMEASURES

Maximum Budget $M = 2825
Baseline NII % = 2.11

Countermeasures (Percent of Budget)

Airport Class	Budget $M	NII %	Technology Options TA	TE	TL	TN	Land Use Options LA (Soundproofing) 5 dB	10 dB	15 dB	LC (Relocation)	Cost Benefit Ratio	Rank
			(Reference Table 25)									
All	2825	1.29	-	NA	-	-	65	23	1	12	122	
		1.62	79		-	-	18	2	-	1	202	
		1.25	-		2	-	65	23	1	10	116	1
		1.57	79		2	-	16	2	-	1	186	
		1.37	-		-	19	56	14	3	8	135	
		1.80	79		-	19	2	1	-	-	327	
		1.33	-		2	19	56	12	3	8	128	2
		1.78	79		2	19	-	-	-	-	299	3

Technology Options:

TA - Refan 2LN1 Fleet
TE - Replace 2LN1 Fleet by 2LN2
TL - Retrofit 3HW1 with LDN
TN - Retrofit 4HW1 with LDN

TABLE 29

NOIZOP RESULTS FOR CLASS All AIRPORTS, PLANNING YEAR 2000, ALL COUNTERMEASURES

Maximum Budget $M = 9313
Baseline NII % = 3.21

Airport Class	Budget $M	NII %	Countermeasures (Percent of Budget): Technology Options (Reference Table 25)				Land Use Options: LB (Soundproofing)				Cost Benefit Ratio	Rank
			TC	TM	TO	TP	5 dB	10 dB	15 dB	LD (Relocation)		
All	9313	1.19	-	-	-	-	42	40	10	8	49	1
		1.37	20	-	-	-	36	31	6	8	54	
		1.20	-	4	-	-	43	36	9	8	50	2
		1.38	20	4	-	-	33	29	6	8	55	
		1.24	-	-	6	-	43	34	9	8	51	
		1.43	20	-	6	-	33	29	5	7	56	
		1.25	-	4	6	-	40	34	8	8	52	3
		1.44	20	4	6	-	31	28	5	7	57	4
		2.14	-	-	-	70	20	6	0	4	94	
		2.66	20	-	-	70	7	1	0	2	182	
		2.16	-	4	-	70	17	5	0	4	98	
		2.76	20	4	-	70	4	1	0	1	220	

TABLE 29 (continued)

Maximum Budget $M = 9313
Baseline NII % = 3.21

Countermeaures (Percent of Budget)

Airport Class	Budget $M	NII %	Technology Options: TC (Reference Table 25)	TM	TO	TP	Land Use Options: LB (Soundproofing) 5 dB	10 dB	15 dB	LD (Relocation)	Cost Benefit Ratio	Rank
		2.27	-	-	6	70	15	5	0	4	106	
		2.89	20	-	6	70	4	0	0	0	313	
		2.32	-	4	6	70	15	3	0	2	112	
		3.05	20	4	6	70	0	0	0	0	610	

TABLE 30

RELATIVE NOISE IMPACT RANKING OF AIRCRAFT IN EACH OF THE PLANNING YEARS

Baseline NII and Source Rankings

Airport Class	Planning Year	Baseline NII Percent	Sources Ranked According to Contribution to NII, Most Offending on the Left							
1	1980	10.44	7	4	5	1	8	10	2	15
	1990	8.78	5	7	8	15	2	10	13	19
	2000	7.42	5	21	15	8	10	22	7	17
2	1980	6.86	4	5	7	1	8	2	10	15
	1990	4.97	5	8	2	7	15	10	13	19
	2000	5.05	5	21	15	8	10	13	22	17
3	1980	8.90	4	5	7	1	8	2	10	15
	1990	6.54	5	7	15	8	2	10	13	17
	2000	6.87	5	21	15	7	17	13	8	10
4	1980	2.39	4	1	5	7	2			
	1990	1.93	5	7	15	2	13	17	12	8
	2000	2.22	21	5	15	13	7	17	8	2
All Together	1980	5.84	4	5	7	1	8	2	10	15
	1990	4.45	5	7	2	8	15	10	13	19
	2000	4.49	5	21	15	8	13	7	10	17

Marginal Benefits of "Deep Cutback" Takeoff Procedure (Countermeasures FA, FB, FC)

NII with "Deep Cutback" Percent	Change from Baseline Percent	Sources Ranked According to Contribution to NII, Most Offending on Left							
9.88	0.56	7	4	5	1	8	10	2	15
8.33	0.45	5	7	8	15	2	10	13	19
7.14	0.28	21	5	15	8	10	22	7	17
6.19	0.67	4	7	5	1	8	2	10	15
4.44	0.53	5	8	2	7	15	10	13	19
4.67	0.38	5	21	15	8	22	13	10	17
8.04	0.86	4	5	7	1	8	2	10	15
5.87	0.67	5	7	8	15	2	10	13	17
6.36	0.51	5	21	15	17	7	8	13	10
2.08	0.31	4	1	5	7	2			
1.68	0.25	5	7	15	2	13	17	8	12
2.05	0.17	21	5	15	13	7	17	8	2
5.29	0.55	4	7	5	1	8	2	10	15
4.01	0.44	5	7	8	2	15	10	13	19
4.18	0.31	5	21	15	8	13	17	7	22

Benefits of All "Free" Countermeasures (TF, TH, TJ, TS, TU, FA, FB, FC)

Airport Class	Planning Year	NII with "Deep Cutback" Percent	Change from Baseline Percent	Sources Ranked According to Contribution to NII, Most Offending on Left							
1	1990	5.13	3.65	12	8	2	15	10	19	13	18
	2000	6.09	1.33	12	15	8	10	22	19	20	
2	1990	2.34	2.63	12	2	8	15	10	13	19	18
	2000	3.42	1.63	21	15	12	8	22	13	10	2
3	1990	3.21	3.33	12	8	15	2	10	13	19	18
	2000	5.05	1.82	21	15	12	8	13	10	22	18
4	1990	0.63	1.30	12	15	2	13	8	18	19	
	2000	1.50	0.72	21	15	12	13	18	8	2	22
All together	1990	2.11	2.32	12	8	2	15	10	13	19	18
	2000	3.21	1.28	21	15	12	8	13	22	10	18

[illegible]

A/C	Class	A/C	Class	A/C	Class	A/C	Class
1	[illegible]	7	[illegible]	13	[illegible]	19	[illegible]
2	[illegible]	8	[illegible]	14	[illegible]	20	[illegible]
3	[illegible]	9	[illegible]	15	[illegible]	21	[illegible]
4	[illegible]	10	[illegible]	16	[illegible]	22	[illegible]
5	[illegible]	11	[illegible]	17	[illegible]	23	[illegible]
6	[illegible]	12	[illegible]	18	[illegible]		

- The national airport network was broken down into four classes, each represented by three or four sample airports, for a total of 14 airports (Table 19).

- The random sample of population cells (total of 929 cells) was representative of the national distribution of population around airports.

- The set of countermeasures defined in Table 25 described a complete collection of national noise abatement options.

- The relative relationships between the cost data associated with the countermeasures was a valid one and would not change with time. It was not necessary for the cost data to be absolutely correct for the study to be valid since preferences for one or the other countermeasures were determined on the basis of relative cost/benefit comparisons. The study would be invalidated if, for some unforeseen reason, the inflation rate for real property (influencing the cost of land use options) would be radically different from that for manufactured items (influencing the cost of aircraft).

Therefore, forecasts do not necessarily represent the present (October 1981) situation.

Countermeasures FA, FB, FC, TF, TH, TJ, TS, and TU (see Table 25 for decoding of countermeasure codes) were found to be attainable at a net cost savings with minimal expenditures.

FA, FB, and FC: Use of "deep cutback" takeoff procedure. It has been shown by an across-the-board application to the airport network sample that the use of a "deep-cutback" procedure for departing aircraft has significant benefit, relative to the baseline "maximum climb" case, in reducing the aggregate noise impact. This benefit is especially realized if applied to the 1980 and 1990 planning year scenarios, but diminishes as changes to the national fleet are introduced by the year 2000.

TF, TH and TJ: Replacement of the 3LN and 4LN aircraft. In effect, the technical options denoted as "replacement of aircraft" have been included to accommodate situations where particular classes of aircraft are projected to be the most offending in terms of their contribution to NII in 1980 and future planning years, and where the technical improvements considered herein are not sufficiently effective to diminish their impact rating to a level comparable with other contemporary classes. It was estimated earlier in this study that a change (by replacement or other means) to a more contemporary technology would be highly cost-effective because of the associated fuel-efficiency improvements. This

option has been examined for 3LN and 4LN aircraft, and was found to have negligible effect on the relative tradeoff of other options discussed in this report.

TS and TU: Build 2HW2 with long duct nacelle (and other associated hardware) by 1990 and 2000. The analysis shows that so equipping 2HW2s will result in a net cost saving in addition to reducing noise exposure. This configuration should therefore be encouraged.

Countermeasures Requiring Expenditures

This discussion concerns countermeasures TA, TB, TE, TL, TN, LA, and LC for 1990, and TC, TD, TG, TM, TO, TP, LB, and LD for 2000 (see Table 25). Options TL and TM, involving the retrofitting of 3HW1s with LDN (and other improvements) in 1990 and 2000 respectively, always ranked first or second in the tradeoff analyses since their costs were relatively small and the benefits very noticeable. Frequently, the combination of TN and TO options (4HW1 retrofit) with TL or TM trailed very closely. However, of all options, the benefits accrued by use of a selective strategy involving a mixture of (a) improvements to home insulation (LA and LB) and (b) relocation of residents to less noise-impacted regions (LC and LD) were the most cost-effective options.

ESTIMATION OF FAR PART 36 NOISE CERTIFICATION LEVELS FOR FUTURE AIRCRAFT

For the representative aircraft of this study, FAR Part 36 takeoff and sideline average noise level was plotted versus maximum certificated takeoff gross weight in Figure 9. The "technology lines" are clearly discernible: old, current, and advanced technologies. Figure 9 also shows Stage 2 and Stage 3 lines for LTOSL (average takeoff certification levels) as derived from FAR Part 36 takeoff and sideline noise limits. These do not exhibit the same slope as the technology trend lines. Any new certification goals should be expressed with that slope as far as takeoff/sideline is concerned. Such an estimated forced slope Stage 3 line is also shown in Figure 9. In Figure 10, the Stage 3 technology line from the previous figure has been repeated, with a new Stage 4 certification goal. This goal is based solely on "technological practicability" since technology-type data only has entered into the goal's derivation.

It was difficult to introduce economic reasonableness into the certification goals derivation process as a constraint on technological practicability. Certification applied to new aircraft, and the economic tradeoff analysis conducted, considered very few technology options at the design state of new aircraft, but concerned itself with retrofits and replacements of existing and future aircraft. However, since the advanced technology consisted mainly of fitting engines with long duct nacelles, improved acoustical treatment and a jet exhaust mixer, and since retrofitting was more costly than incorporating such features at the design stage, it appeared reasonable to conclude that the FAA should encourage the incorporation at such features on newly designed aircraft by adopting the Stage 4 limits in Figure 10.

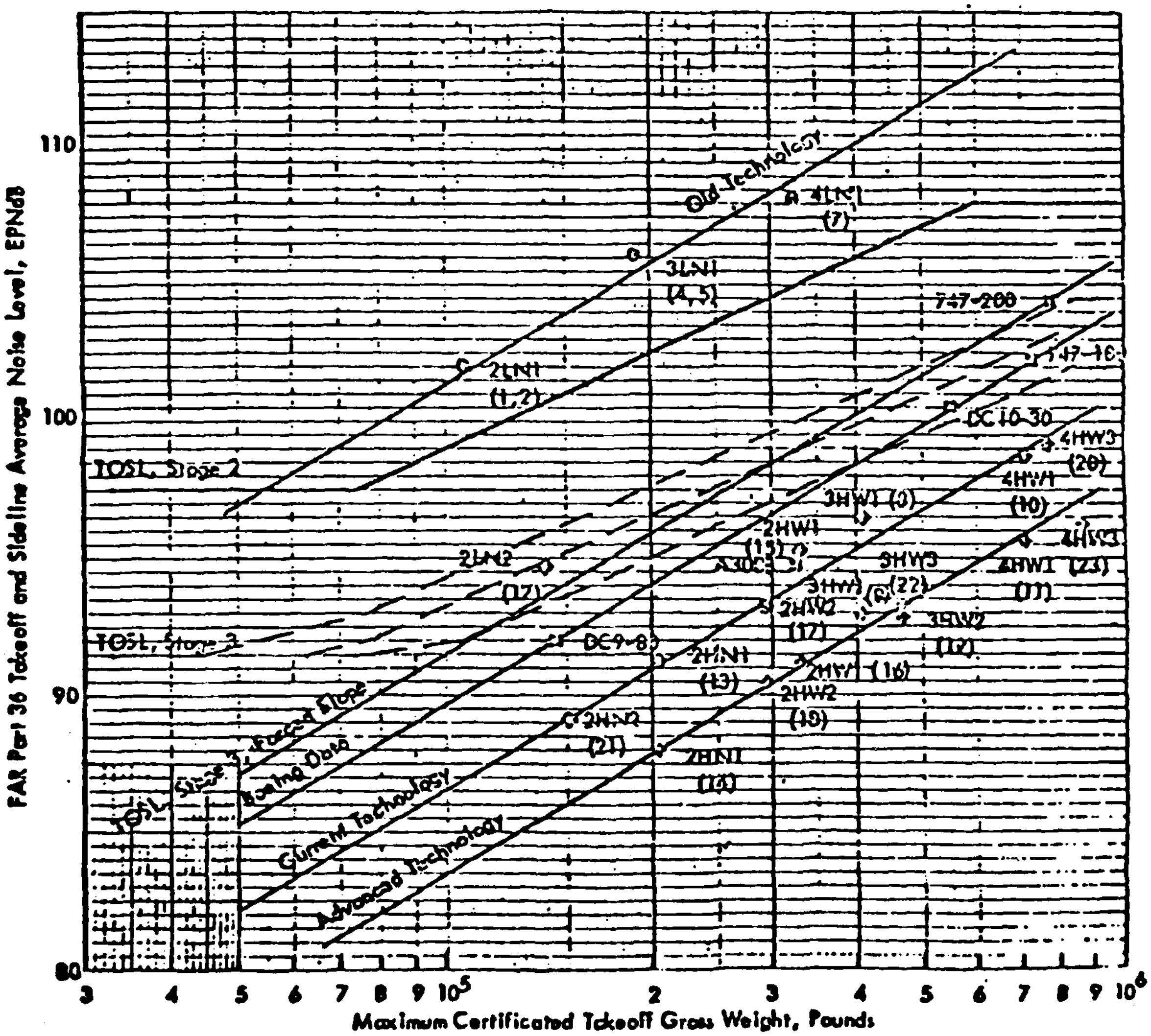


Figure 9. LTOSL (Takeoff and Sideline Average Level) versus Weight Showing "Technology Lines." Circles: Old Technology Aircraft, Diamonds: Current Technology, Stars: Advanced Technology, Crosses: Independent Backup Data.

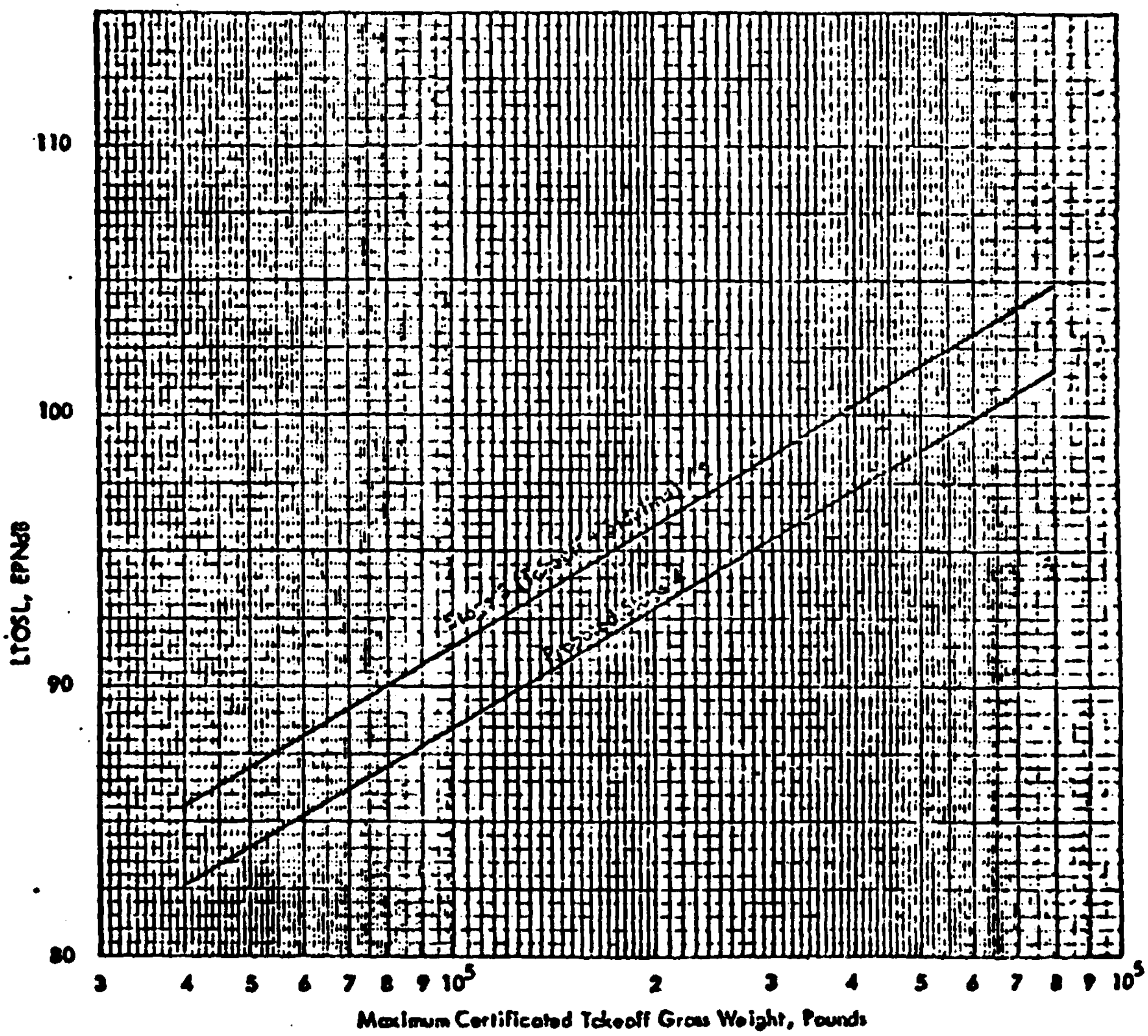


Figure 10. Definition of Stage 4 Certification Goal Based on Technological Practicability Only

SECTION 8

CONCLUSIONS

This study examined the current and projected air carrier jet fleet, the U.S. airport network and the noise-impacted airport neighborhoods as a "system," within which various noise reduction options were selected for tradeoff analysis based on their cost-benefit relationships.

The examination of source technology was based on a set of representative current and future aircraft types, each of which was scrutinized in terms of its noise impact on the nation. The potential benefits to be accrued by application of additional noise controls to these aircraft were compared in cost-effectiveness terms with those of flight path (departure-operation) changes and land use options (sound insulation of dwellings and relocation of residents). The primary findings of the study were:

TECHNOLOGY OPTIONS

Air Carrier Aircraft

The introduction of high bypassed engined aircraft to the fleet by the year 1990, taken as a baseline development of the fleet, was projected to provide a major reduction in noise impact. All of the high bypass retrofitted aircraft with the long duct nacelles and mixers would be fuel efficient and would have more range capability than the baseline aircraft because of increased aerodynamic and propulsive efficiency. The new aircraft in 1990 and 2000 would have the benefit of increasingly advanced technology and these advantages would result in a significantly lower fuel burned per pound of payload per nautical mile. The most promising noise reduction alternatives appeared to be the new aircraft which are expected to utilize the refan, high bypass-ratio, and clip-fan engine technology and new aircraft equipped with long-duct nacelle and mixer configurations. Application of further technological improvements to this fleet might provide a significant, but smaller, reduction in noise impact.

The major noise impact contributors would continue to be the current narrow-bodied, low bypass engined aircraft, even after application of available technology (quiet nacelles, refanned engines) to these aircraft. If all practical technologies were to be applied to the fleet by the year 1990, further benefits would not be expected in the following decade (i.e., to the year 2000), except by replacement of the most-offending aircraft.

General Aviation Aircraft

For propeller aircraft reduced rpm to achieve noise reduction had less adverse impact on performance than did reduced propeller diameter. If

feasible, propellers that produce more thrust per horsepower than current production designs would be more desirable to minimize performance deterioration. One approach to recover performance losses when using a slower rpm would be to increase propeller diameter as diameter has a strong influence on low speed performance. To accommodate larger propeller diameters would require new longer gears and new gear well configurations and the performance losses may not be totally recoverable because of these
and the performance losses may not be totally recoverable because of these
weight and design changes. A critical factor involved in achieving reduced noise levels through lower tip speeds is the availability of suitable engines. The majority of the propeller aircraft U.S. fleet have engines rated at 200 horsepower or less. No certified gear engines are now in production in this low power class.

Helicopters

For the year 1980, helicopters were classified in four groups -- light, medium, heavy single, and heavy tandem rotors -- with different missions. However, for the year 1990 and year 2000 helicopters, the missions were kept constant. The gross weight of the future helicopters was allowed to increase from the corresponding 1980 gross weights, similar to the prevailing trends of helicopter growth. The economics were significantly affected by incorporating quiet design features on future helicopter systems.

Noise Certification

A critical review of the basic concepts involved in noise certification showed that the existing method has been successful as a control of aircraft technology to limit source noise but has not always provided a consistent basis for evaluating changes in noise impact in airport communities.

In terms of FAR Part 36 noise certification levels, based on plots of FAR Part 36 takeoff and sideline average noise level versus maximum certificated takeoff gross weight, a new Stage 4, 3 dB lower than the current Stage 3, was estimated as being effective by the year 1990. There was no available information to justify a projection of further reductions through the year 2000. Since very few technology options were considered at the design stage of new aircraft in this study, which concerned itself with retrofits and replacements of existing and future aircraft, it was concluded that the FAA should encourage the incorporation of such features as long duct nacelles, improved acoustical treatment, and jet exhaust mixers on newly designed aircraft by adopting the Stage 4 limits.

FLIGHT PATH OPTIONS

An across-the-board application to the airport network sample showed that the use of a "deep-cutback" procedure for departing aircraft had a significant benefit, relative to the baseline "maximum climb" case, in reducing the aggregate noise impact. This benefit was applicable to the 1980 and 1990 planning years scenarios, but diminished as changes to the national fleet were introduced by the year 2000.

LAND USE OPTIONS

Benefits accrued by use of a selective strategy involving a mixture of (a) improvements to home insulation and (b) relocation of residents to less noise-impacted regions were found to be the most cost-effective options.

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